On What There Is according to Quantum mechanics

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Abstract

In this essay I make use of the resources of 'naturalized ontology' in order to determine what quantum mechanics implies about answers to fundamental metaphysical questions. Naturalized ontology is a methodology for metaphysics influenced by the philosopher Willard Van Orman Quine which makes explicit reference to our best scientific theories in order to answer questions which have traditionally been reckoned to belong solely to the realm of philosophy such as 'What is the nature of reality in the most general sense?' Quantum mechanics faces a unique interpretational problem known as the 'measurement problem' which makes determining the answer to such general metaphysical questions on this view especially problematic; nevertheless, naturalized ontology interprets and evaluates the various responses to this problem via measures of 'theoretical virtue', and ultimately concludes that the best interpretation of quantum mechanics—and thus reality—is absurd.

On What There Is according to Quantum mechanics

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Part 1: Introduction

Influenced by by W. V. Quine's philosophy of science and metaphysics, the methodology of naturalized ontology is one of looking at the best physical theories available as a guide to fundamental metaphysical questioning.[1] 'Naturalism' according to Quine is "the recognition that it is within science itself, and not in some prior philosophy, that reality is to be identified and described." (Quine 1981, p. 21) Because naturalism entails the "abandonment of … a first philosophy prior to natural science" (Quine 1981, p. 67) it justifies itself from within as the best available standpoint from which to seek knowledge: "we seek no firmer basis for science than science itself [insofar as] we are free to use the very fruits of science in investigating its roots." (Quine 1995, p. 16) 'Philosophy' from a naturalistic standpoint is simply "natural science trained upon itself and permitted free use of scientific findings." (Quine 1981, p. 85) Since quantum mechanics is arguably the current exemplar of a scientific theory, then laying my cards on the table at the earliest available opportunity, I want to make it clear that the guiding question of naturalized ontology will be:

> What does quantum mechanics (as our best physical theory) say about the nature of reality in the most general sense?

Naturalized ontology means assuming outright that quantum mechanics corresponds to reality in some way in order to see what metaphysical implications follow. What this means in practise is assuming that quantum mechanics tracks the state of the world in a truthful way. This means that—initially at least—we will not be considering interpretations of quantum

[1] Because naturalized ontology means looking at our best physics, what this entails in practice a lot of the time is looking at the *most up-to-date* physics, so in this thesis I will endeavour to refer to the most recent research and developments in the (philosophy of) physics literature, at least as far as I am aware of it.

mechanics which treat it merely instrumentally, for example Born's statistical interpretation which interprets the quantum wave function epistemically—rather than ontologically—as a tool for calculating the probabilities for measurement outcomes in quantum experiments.[2]

Working out what quantum mechanics says about the nature of reality in this sense partly entails providing a specific explanatory account of the connection between, to use Wilfrid Sellars's terms, the 'scientific' image of nature provided by quantum mechanics and the 'manifest' image of everyday experience (Sellars 1962). As an example of how such an enterprise proceeds, consider another paradigm where giving such an account is relatively intuitive and straightforward: classical mechanics. In this theory the scientific image of the world is given by a 'primitive ontology' (Allori 2013) whose variables range over microscopic material particles; the manifest image of everyday objects such as chairs, cats, and stars then reduces to the histories of these primitive variables at some macroscopic limit (Allori 2013, pp. 67-68).

Unfortunately, things aren't quite so clear-cut in the case of quantum mechanics where, despite its being one of the most accurate, explanatorily powerful, and well-verified (in a word: successful) physical theories ever discovered[3], and furthermore being roughly a century old, there is *still* major disagreement over foundational issues. This is partly because it is not at all clear what quantum mechanics is really *about*, due to disagreement between physicists and philosophers regarding fundamental meta-physical issues. As an informal presentation of this state of affairs, consider the following: at a conference on the foundations of quantum mechanics called 'Quantum Physics and the Nature

[2] For what it's worth, this assumption should not be mistaken for a genuinely-held belief on the part of the author about quantum mechanics's correspondence with reality, either (that is, the author is not necessarily a 'true believer' in quantum mechanics, as will become apparent).

[3] Non-classical phenomena quantum mechanics was developed in order to explain include black-body radiation, the photoelectric effect, and electron diffraction, among others.

of Reality' held in July 2011, a poll was taken, and the results were subsequently written up in a paper.[4] Note that there were only 33 respondents to the poll among those who attended the conference, so it should not be considered a definitive survey by any means; nevertheless, it suggests a decent snapshot of the current situation regarding quantum foundations. Tellingly, for our purposes, is the fact that one of the questions on the poll was 'What is your favourite interpretation of quantum mechanics?' '*Favourite interpretation'*? Such subjective-seeming concepts surely cannot be relevant to physics, since physics is meant to be as objective a science you can imagine. What is meant by these worrying terms in this context? The short answer is that, if quantum mechanics is taken to represent reality, then it is not at all clear what this could possibly mean, due to the fact that the mathematical structure of the theory does not suggest a definitive, clear-cut explanation of what the world world *must* be like in order for it to be so successful. This is because quantum mechanics has a number of empirically indistinguishable[5] yet ontologically divergent 'interpretations', each of which was developed in response to a problem known as the 'measurement problem' which is, in the words of Sheldon Goldstein, "*the* conceptual difficulty" (Goldstein 2013, emphasis original) afflicting quantum mechanics.

The measurement problem essentially arises due a proposition about quantum mechanics we assumed at the start of this essay: that it represents reality. In practice what this entails is that it should be interpreted realistically as a theory about the nature and behaviour of an entity known as the 'wave function'. Understood in this way, the measurement problem is a paradox about the connection between what quantum mechanics predicts when the wave function is taken to represent the complete reality of physical systems and what is actually observed when measurements are performed on these systems

[4] Schlosshauer, Kofler, and Zeilinger 2013.
[5] Although not really—more on this in a later section.

(Wallace 2013, p. 7). The problem is that the dynamical law guiding the behaviour of the wave function and which arguably explains the aforementioned non-classical phenomena quantum mechanics was developed in response to also entails that the wave function evolves into physical states that are in direct conflict with what is experienced. Alyssa Ney provides a succinct diagnosis of the problem:

> “The trouble is that what the laws of quantum mechanics predict is very strange and … appears to be in conflict with what we actually observe when we take measurements” (Ney 2013a, p. 24).

It is thus the measurement problem which gives rise to the infamous foundational enterprise of ‘interpreting’ quantum mechanics: each class of solutions to the measurement problem—and there are a few!—is roughly considered to be its own, mutually-exclusive ‘interpretation’ of quantum mechanics, hence why the attendees at the conference on quantum foundations were polled on their ‘favourite interpretation’.[6]

As Craig Callender (2009) points out, any realistic solution to the measurement problem will come with its own background metaphysical assumptions, including a distinct set of ontological commitments, the nature and dynamics of which will in turn imply answers to long-standing metaphysical questions regarding, for example, the problem of determinism and free will, the nature of space and time, the connection between mind and world, among other things. This being the case, it is perhaps more accurate to say that each solution to the measurement problem—insofar as each is, roughly speaking, committed to a different ontology and different laws specifying how this ontology evolves

[6] Interestingly, 58% of physicists surveyed at the same conference responded to the question “How much is the choice of interpretation a matter of personal philosophical prejudice?” with the answer “A lot” while 27% of them responded with the answer “A little” (Schlosshauer, Kofler, Zeilinger 2013, p. 9).

dynamically in time, and so on—will itself suggest a more general background fundamental metaphysical ‘interpretation’ about the nature of reality as a whole in general, rather than merely quantum mechanics in particular.[7]

So insofar as we are assuming quantum mechanics represents the nature of reality in order to figure out what metaphysical implications follow, and because each interpretation of quantum mechanics comes with its own distinct set of metaphysical ‘baggage’ (Tegmark 2008), this means that, in order to see what picture of reality follows from quantum mechanics, we are compelled to address the measurement problem, and determine the best way to deal with it. As Ney puts it:

> “Anyone who wants to understand quantum mechanics as a theory of our world (i.e. anyone who wants to be a realist about this theory) … must do something to reconcile what the theory predicts with what we observe.” (Ney 2013a, p. 24)

1.1: Is quantum mechanics underdetermined by empirical evidence?

Before moving on, I first want to address an oft-cited misconception about quantum mechanics which is that its different interpretations—despite the fact that such approaches entail drastically different pictures of reality as a whole, completely ontologically at odds with eachother—are experimentally indistinguishable from one another and that quantum mechanics is therefore underdetermined by empirical evidence as a consequence. This common misconception is nicely summed up by Holger Lyre when he states that the various interpretations of quantum mechanics are “empirically equivalent, but ontologically different.” (Lyre 2010, p. 1432) That is, according to Lyre, quantum

[7] In other words: arguably the ‘interpretations’ of quantum mechanics are distinct meta-physical theories which come with their own sets of assumptions and prejudices about the connections between theory and experience and indeed about the nature of reality as a whole.

mechanics is underdetermined owing to the supposed fact that each of its interpretations entail the same corpus of empirical data. This state of affairs (as he sees it) leads Lyre to posit the following principle about quantum mechanics:

> "Call this QTUD: the underdetermination of quantum theory by empirical evidence as displayed in the multitude of rivaling interpretations." (Lyre 2010, p. 1434)

Lyre cites this as a particular example of what he calls more generally the 'thesis of theory underdetermination':

> "TUD-Thesis: For any theory T and any body of observation O there exists another theory T', such that T and T' are empirically equivalent (but ontologically different)." (Lyre 2010, p. 1433)

Regarding this "multitude of rivalling interpretations", Lyre cannot envision *any* future empirical evidence being brought to bear in deciding between them, as his TUD-Thesis considers underdetermination of theory by evidence even in the context of "*all* possible (past and future) observations." (Lyre 2010, p. 1433, emphasis added) Although Lyre is correct in pointing out that the interpretations of quantum mechanics entails "heterogeneous ontological pictures of the world" (Lyre 2010, p. 1432), he is nevertheless emphatically incorrect in his claim that the all of these interpretations are empirically underdetermined in the case of *all* future data. The most clear example of this—an example which we will address in much more detail in a later section—concerns 'collapse' theories which are actually empirically *inequivalent* to other quantum interpretations insofar as they do not in fact "satisfy the same corpus of observational data" (Lyre 2010, p. 1432) as them. For example, dynamical collapse theories make clear empirical predictions which can—in principle at least if not always in practice given the limitations of current technology—be put to the test, specifically predictions regarding whether states of quantum superposition can persist past some macroscopic limit. Indeed, according to the physicist Giancarlo Ghirardi:

> “Collapse theories qualify themselves as rival theories of quantum mechanics and one can easily identify some of their physical implications which, in principle, would allow crucial tests discriminating between the two.” (Ghirardi 2011)

Now, although it is clear that Lyre’s QTUD principle—the misconception about *all* the interpretations of quantum mechanics being empirically underdetermined in the case of *all* future data—is misguided, at the same time this is not to deny that there are interpretations of quantum mechanics which *are* in fact empirically-indistinguishable from one another. For example hidden variables theories and no-collapse theories are indistinguishable in the sense that they entail the same corpus of empirical data, insofar as there is no experiment one could perform that would constitute evidence for one over and above the other. For naturalized ontology, then, in cases where there is no such experimental data available to decide between them, theories are evaluated via supra-empirical measures of theoretical virtue, specifically parsimony and explanatory power.

Taking all this into account, then, the modus operandi of naturalized ontology becomes: if you want to work out the nature of reality in a general sense, then you had better first work out what the best way to conceive of the connection between theory (scientific image) and experience (manifest image) on the quantum mechanical picture is. In essence this means directly addressing the measurement problem and evaluating the responses to it, in accordance with uncontroversial, objective criteria of theoretical virtue, summed up in the proposition that the best theory is the one which is the most parsimonious, explanatorily powerful, and most consistent with all the available empirical data.

Part 2: The state of the quantum world

Before we move on to examining and evaluating the competing interpretations of quantum mechanics we will first examine how it was developed in its (rough) historical context, specifically with regard to how the course of this development lead physicists and philosophers straight to the measurement problem.

In order to clearly illustrate the novel conceptual features of quantum mechanics, i.e. those features which render it seemingly anomalous from the perspective of the previously prevailing paradigm of classical mechanics, we will examine two phenomena which seemingly necessitate a non-classical representation, namely ‘interference’[8] and ‘entanglement’[9], discovered and verified time and time again in quantum experiments.

2.1: Superposition

To begin with, the ability of quantum systems to exhibit the phenomenon of ‘interference’ arguably cannot be understood if they are thought of as being made up of discrete entities which exist in definite classical states. Quantum interference is perhaps most vividly demonstrated in the infamous double-slit experiment.[10] In this experiment light is shined toward a screen with two vertical slits cut into it onto a photographic plate behind. The light projects alternating dark and bright bands onto the plate: an interference pattern. Thomas Young, who first ran the experiment in the 19th century, explained this interference

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[8] According to Richard Feynman, quantum interference is “a phenomenon which is impossible, absolutely impossible, to explain in any classical way, and which has in it the heart of quantum mechanics. In reality it contains the only mystery.” (Feynman 1963, p. 37)

[9] “I would not call [entanglement] one but rather *the* characteristic trait of quantum mechanics, the one that enforces its entire departure from classical lines of thought.” (Schrodinger 1935, p. 555)

[10] For Ghirardi it is “interference experiments [that] verify quantum mechanics” (Ghirardi 2011) *per se*.

pattern by postulating that light is a wave and stating that the two slits on the screen cause the light waves to overlap and their amplitudes to interfere as they pass through them: bright bands correspond to crest-crest interference where the amplitudes of the wave are reinforcing eachother whereas dark bands correspond to crest-trough interference where the amplitudes are cancelling eachother out. In 1905, however, Albert Einstein's demonstration of the photoelectric effect (the ability of photons to bump into electrons and knock them out of their shells i.e. where they orbit around the nucleus of an atom) proved that light comes in discrete—or quantized[11]—packets (particles) called photons. This fact suggested a variant of the double-slit experiment where the light could be sent through the slits a single packet of light at a time. This was realized in 1909, when a physicist named Geoffrey Taylor ran the double-slit experiment with individual photons and recorded, dot-by-dot, where each of them landed on the photographic plate behind the screen. Taylor found that over time the same interference pattern of alternating bright and dark bands was projected onto the photographic plate: the smoking gun for wave—not particle—behaviour. This result completely baffled contemporary physicists because it was contrary to their classical expectations, which dictated that the discrete photons would follow definite trajectories through either of the slits to the exclusion of the other and deposit on the photographic plate over time as two narrow bands of light directly opposite each slit.

Nevertheless, the textbook explanation of the interference pattern appearing in the case of the version of the double-slit experiment performed with discrete photons which came to be accepted by quantum physicists is that, since there is nothing else for the single photons to interfere with, then they must actually be travelling through both slits at the same time and interfering with *themselves*. That is, the observed interference patterns suggest that each single photon

[11] Hence 'quantum' mechanics.

follows multiple trajectories from the coherent light source, travels through both slits which causes them to interfere with themselves like waves do, and finally lands on the photographic plate, causing the familiar interference patterns as evidence of this. In these contexts, it doesn't make sense to ask which slit the photon 'really' went through because interference seems to suggest that the photon does not go through *either* the left slit *or* the right slit to the exclusion of the other, as would a classical particle following a definite trajectory, but rather goes through *both* the left slit *and* the right slit *at the same time*, like a wave, or in Quantumese follows a 'superposition' of trajectories:

> "Most experiments aiming to verify that a particle is in a quantum superposition of states look for evidence of interference." (Knee 2015)

Interference is thus a specific example of the phenomenon of quantum superposition. Superposition more generally refers to the ability of quantum systems such as photons to do multiple, even contradictory things at once, for example, occupy two different positions simultaneously or even move and stay stationary at the same time. It is important to note that superpositions aren't just confined to e.g. position and momentum states; in quantum mechanics many physical variables—not just position—can take on combinations of values. For example quantum entities can also be in superpositions of energy levels, 'spin' states, and so on. Superposition states thus forced early quantum physicists to come up with a novel way of representing quantum entities because superpositions are combination (*both* x *and* y) states e.g. being in multiple places (*both* here *and* there) at the same time.

2.2: Entanglement

Entanglement is a phenomenon first described by the physicist Erwin Schrodinger in 1926. In a later paper, Schrodinger describes entanglement in the following way:

> “When two systems, of which we know the states by their respective representatives, enter into temporary physical interaction due to known forces between them, and when after a time of mutual influence the systems separate again, then they can no longer be described in the same way as before, viz. by endowing each of them with a representative of its own. … By the interaction the two representatives have become entangled.” (Schrodinger 1935, p. 555)

Entanglement is a form of strong nonclassical correlation between spatially separated quantum systems which emerges under certain circumstances when distinct physical systems (such as two particles or even a particle and its environment) interact, and which persists even when these systems are separated in space. Entanglement is distinguished from mere classical correlation due to the fact that entangled entities are strongly correlated in a *superposition* of ways, such that the behaviour of the unified system is no longer describable classically, e.g. in terms of the interactions between definite particles with their own individual identities. Thus, in mathematical terms, for entangled physical systems, the “states of [the] composite system … cannot be expressed as direct products of quantum states of the individual components.” (Shimony 2009) There is more information contained within state of the unified, entangled physical system than in the conjunction of the components which make it up. In other words, when entities become entangled, the correlation between the individual components contains all of the information whereas the components contain none (or very little) in themselves.

2.3: The wave function

The ‘wave function’

$$\psi$$

is the entity used to represent quantum entities insofar as wave functions explicitly represent superposition and entanglement states.[12] The reason wave functions represent superposition states is because they are essentially distributions of complex-valued ‘amplitudes’ over a state space called ‘configuration space’, where each amplitude assigned to a point in configuration space corresponds to a distinct possible configuration a physical system can be in. Interference in quantum experiments is accounted for by the ‘interference term’ of the wave function which is a “phase relation” (Bacciagaluppi 2012) which links the distinct terms of the wave function in order to account for the interference between them (Bacciagaluppi 2012). Likewise, the reason entangled states must be represented by the wave function is because—to put it crudely—an entangled system is more than the sum of its parts, and as a consequence of this:

> “[I]t is argued that entangled states cannot be adequately characterized in terms of states of entities living in familiar, three-dimensional space; rather, they must be characterized as states of something—namely, the wave function—spread out across a higher-dimensional (configuration) space” (French 2013, p. 78).

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[12] Yet note that it is not just the phenomena of superposition and entanglement that imply a wave function representation for quantum entities. For example according to Valia Allori, “results … such as Heisenberg’s uncertainty principle … were taken to show that quantum theories had to be about the wave function, not about particles.” (Allori 2013, p. 67)

That is, the components of a strongly-correlated, interacting (i.e. entangled) quantum state are interwoven and inextricable, and share a unified wave function, which “combines—or binds—[them] into a single irreducible reality.” (Goldstein 2013)

The dynamics of quantum systems are determined by the ‘Schrodinger equation’

$$\hat{H}\psi = -i\hbar \frac{\delta\psi}{\delta t}$$

which is the law governing the evolution of the wave function over time. The future state of a quantum system is calculated by plugging the Hamiltonian of its wave function (which represents its total energy at a point in time) into the Schrodinger equation; the solution to this equation outputs the state of the system in the future (Adler and Bassi 2009, p. 1). In order to account for superposition states such as interference effects the Schrodinger dynamics are ‘linear’ (Barrett 2014), which means that, given multiple solutions to the equation, then any sum of those solutions is itself a solution. Indeed, according to Simon Saunders, linearity is also known as the ‘superposition principle’, which he describes as the principle that any combination of quantum states is itself a valid state (Saunders 2010 pp. 2-3).

Part 3: The measurement problem

OK, so far so good. Due to entanglement and interference, almost no-one has a problem with the idea that physical systems must—in some contexts, at least—be represented by the wave function evolving according to the linear dynamics, as opposed to some classical state evolving according to classical laws.[13] However, there is a major problem associated with taking the wave function to fully represent the reality of such systems insofar as the linearity of the Schrodinger equation determining the wave function's dynamics entail that it evolves into states that are inconsistent with experience; this is because linearity ensures that terms in superposition states can never "drop away" (Ney 2013a, p. 21). Ney elaborates:

> "[D]ue to the linearity of the Schrödinger equation, systems in superpositions of (say) position never evolve out of these superpositions—what corresponds to terms in the sum do not go away." (Ney 2013a, p. 30)

This being the case, then the linear dynamics entail that the states of physical systems should *always* be described by superpositions, which is a problem because such states are never directly observed:

> "[W]e never observe systems in a smeared-out state of being here and there or observe a pointer in a superposition of pointing here and there." (Ney 2013a, p. 30)

Although the linear Schrodinger evolution entails superposition is always preserved and thus that physical systems systems should always be described

[13] The key word here being 'almost'. There are interpretations of quantum mechanics known as 'hidden variables theories' which resist this idea. We will discuss the most prominent of these theories in a later section.

in terms of coherent superpositions, nevertheless these systems are only ever observed to be in definite states when measurements are performed on them (Ney 2013a, p. 24). The measurement problem is thus the problem of reconciling quantum theory's invocation of the linear Schrodinger dynamics needed to account for superposition and always predicting this superposition with the appearance of the definite reality actually experienced when quantum systems are measured (Callender 2009).

To bring it back to the double-slit experiment: in this context, the measurement problem is the problem of accounting for why, if interference suggests that quantum entities move through a superposition of all possible trajectories, and if linearity entails that these entities cannot evolve out of their superposition states, such entities nevertheless appear to exist in definite states when measurements are performed on them. This apparent breakdown of the Schrodinger dynamics is most easily demonstrated if you place a measuring device at the slits in the double-slit experiment set up in order to try and measure which slit the photon 'really' travels through. In this context linearity seemingly breaks down and wave functions, rather than describing superpositions, seem to 'collapse' onto definite states instead.

This version of the double-slit experiment is described by a wave function for a physical system composed of a measuring device 'device' and a photon 'photon'. Initially, device is set up so that it measures the state of photon; photon's state is 'left' if it will travel through the left slit, and 'right' if it will travel through the right slit. There is an observable on device known as its 'pointer state'; the value of this variable before measurement is 'ready' (also referred to as its 'ground state'), whereas the value after measurement can be either 'left' or 'right', depending on the state of photon.

To begin with, device's pointer starts in its ground state, displaying 'ready'

$$|\text{device}>_{\text{ready}}$$

whereas photon is prepared in the superposition state

$$(|\text{photon}>_{\text{left}} + |\text{photon}>_{\text{right}})$$

So the initial state of the system, before measurement, is

$$(|\text{photon}>_{\text{left}} + |\text{photon}>_{\text{right}})\ |\text{device}>_{\text{ready}}$$

The rules of interaction between device and photon are as follows: if, before measurement, photon is in its 'left' state, then after measurement device's pointer state will be 'left'; likewise if, before measurement, photon is in its 'right' state, then after measurement device's pointer state will be 'right'

$$|\text{photon}>_{\text{left}} \rightarrow |\text{device}>_{\text{left}}$$
$$|\text{photon}>_{\text{right}} \rightarrow |\text{device}>_{\text{right}}$$

These rules capture just what a measurement is: device is measuring the state of photon just if there is some observable on device which reliably tracks the state of photon in an appropriate way (Ismael 2009).

If measuring devices are themselves considered to be subject to the linear Schrodinger dynamics[14] then the rules for linear Schrodinger evolution (i.e. the fact that linearity "preserves superpositions" (Ghirardi 2011)) tell us that the joint state of photon and device after interaction is a superposition of states of the the unified system (Ismael 2009). That is, if device measures photon, it follows from

[14] A plausible assumption if you consider that the measuring device is ultimately made of elementary particles (electrons etc.) which themselves obey the laws of quantum mechanics.

the linear dynamics and the rules of interaction between device and photon if device is to be measuring the state of photon that the final state of the system after interaction is the superposition state

$$(|\text{device}>_{\text{left}} + |\text{device}>_{\text{right}})$$

Basically, if photon is in a superposition of different states, then, since linearity means that superpositions are preserved, device should be sensitive to this and register both measurement outcomes. The interaction between device and photon should thus lead to a final state where device is in a linear superposition of registering multiple states of photon. However nobody has ever actually observed a measuring device registering superposition states; what is actually observed (as per device's 'observable' i.e. its 'pointer' state) is *either* the state

$$|\text{device}>_{\text{left}}$$

or

$$|\text{device}>_{\text{right}}$$

If the wave function describes a superposition of going through both slits at the same time, and if the terms in this superposition are prevented from disappearing because of the linearity of the Schrodinger equation, then the measuring device should register a superposition of states: *both* the state where the photon travelled through the left slit, *and* the state where the photon travelled through the right slit. Yet the meaning of such a state of affairs isn't clear because the measuring device always registers definite measurement outcomes instead: *either* the state where the photon travelled through the left slit, *or* the state where the photon travelled through the right slit. That is, only one term in the superposition (corresponding to a definite outcome) is ever observed (Byrne 2010). What this problem corresponds to mathematically is the fact that, in situations which are characteristic of measurement, the interference term in the wave function is no longer needed to build the correct wave function for the physical system under observation; in these contexts some “classical probability formula” (Bacciagaluppi 2012) predicts the observed outcome instead. So understood in this way the measurement problem is essentially the problem of accounting for why quantum theory’s linear dynamics which preserve superpositions break down in contexts that are characteristic of measurement.

To hone in on the problem a little bit: it is in fact the conjunction of the assumptions of the ‘representational completeness of the wave function’ and ‘linearity in all contexts’ that together predict something about the final state of physical systems that is seemingly inconsistent with what is actually experienced insofar as such systems appear to be in a definite (classical) states rather than superposed ones when they are observed (Bub and Pitowsky 2010, p. 438). Insofar as it is these assumptions which entail the measurement problem, it seems that at least one—or perhaps both—of them has to go.

3.1: Orthodox quantum mechanics

As an attempt to solve the measurement problem, the physicist John von Neumann took the strategy of denying the second assumption i.e. ‘linearity in all contexts’; to that end he modified the quantum laws so that the linear Schrodinger dynamics aren’t determining the evolution of physical systems in contexts that are characteristic of measurement. Inspired by the thought that if it is possible (even in principle) for an observer to determine which slit the photon passes through, then the interference pattern disappears (Goldstein 2013), or in other words the idea that quantum entities seemingly only exist in superposition states when nothing is observing them, von Neumann was led to the idea that consciousness plays a central role in quantum mechanics insofar as the act of measurement by a conscious observer apparently marks the point where linearity breaks down and wave functions 'collapse' from superposition states onto definite outcomes.

This supposed 'solution' to the measurement problem is part of von Neumann's 'orthodox quantum mechanics' which is his rigorous mathematical axiomatization of Niels Bohr and Werner Heisenberg's earlier 'Copenhagen' interpretation. According to orthodox quantum mechanics, there are two laws which describe the evolution of the wave function that apply in different contexts: when a system is being observed it evolves according to the 'collapse postulate' (Process 1) into a sharp peak in amplitude localized around a definite measurement outcome via an indeterministic or 'stochastic' process; when a system isn't being observed it evolves according to the Schrodinger equation (Process 2) and behaves in the standard quantum way (i.e. as a linear or coherent process).

On this interpretation, collapse accounts for the manifest image that we all experience insofar as it marks the point of the 'classical limit' i.e. the point at which the quantum (superposed) world transitions into the classical (definite) one.

A major criticism of orthodox quantum mechanics is that it seems to entail that physical systems possess full reality only insofar as they are observed.[15] Yet for many physicists and philosophers—insofar as they are ontological *physicalists*—it is absolutely unacceptable for consciousness or any other dualistic concept to play this sort of role in a fundamental physical theory. More generally, the idea that subjective concepts such as measurement, observation,

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[15] As Einstein famously complained to Niels Bohr: “"Do you really believe the moon exists only when you look at it?”

or consciousness can affect the evolution of the physical wave function in this way is completely mysterious and therefore suspect; for example, observation arguably cannot be a fundamental notion in a physical theory because observers are obviously not fundamental physical entities themselves.[16] Similarly Chris Timpson argues that the principles of physicalism and realism should make us wary about introducing ‘measurement’ as a primitive concept in a fundamental physical theory: measuring devices are themselves made up of particles, and so should be treated as obeying the same dynamical laws as other physical interactions (Timpson 2010, p. 464).[17] Furthermore, von Neumann never quantitatively specifies exactly when a measurement (his Process 1) is happening: there is thus a problem about determining exactly when linearity breaks down on his theory. Thus von Neumann’s collapse postulate doesn’t have the requisite precision to play a fundamental role in a physical theory such as quantum mechanics.

3.1.1: Dynamical collapse

Taking criticisms of orthodox quantum mechanics such as the aforementioned on board—i.e. that it doesn’t suggest a dynamical mechanism which has a basis in precise physical laws which could possibly provide a non-arbitrary explanation for why the breakdown of linearity occurs (Ghirardi 2011)—so-called ‘dynamical collapse’ theories modify the Schrodinger dynamics, making collapse a “natural mechanism” (Ney 2013a, p. 35) caused via, for example, interaction between micro- and macro-systems, rather than via ‘measurement’ which is an inappropriate notion for a fundamental physical theory (Ney 2013a, p. 35).

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[16] A related objection concerns the fact that in orthodox quantum mechanics observers are always treated as external to the physical system under inspection; this has the consequence that orthodox quantum mechanics is essentially an incomplete theory of reality insofar as it cannot be applied to the universe as a whole: how could an observer stand outside the universe?

[17] For more on this point, see Bub and Pitowsky 2010, p. 433

The most well known of these dynamical collapse theories was formulated in 1986 by the physicists Giancarlo Ghirardi, Alberto Rimini, and Tullio Weber (GRW). GRW didn't locate a sharp, distinct boundary between where collapse occurs and where it doesn't; rather they modified the Schrodinger equation "by the addition of stochastic and nonlinear terms" (Ghirardi 2011) in a way such that it applies to all physical systems at all times and yet is also able to account for collapse as an explicitly dynamical, mathematically-precise process. This modification of the quantum dynamics has the consequence that, for all situations except ones that would be characteristic of measuring a physical system such as a measuring device in a state of superposition, the modified equation gives identical results to the unmodified Schrodinger equation. However the predictions of GRW's modified equation depart drastically from the predictions of the Schrodinger equation in situations where one is dealing with a physical system such as a measuring device that is predicted by the unmodified Schrodinger dynamics to be in a state of superposition (Wallace 2013, pp. 7-8); in those situations GRW's stochastic modification of the Schrodinger equation guarantees that the predicted superposition breaks down via a stochastic process of collapse onto peaks in amplitude localized around the observed, definite measurement outcome (Ney 2013b, pp. 170-171).[18] This modification is necessary, in GRW's view, because if the wave function of a physical system such as a measuring device is to provide an accurate description of that system post-measurement, then it had better correspond to the observed (definite) outcome, rather than a superposition of outcomes. As Bacciagaluppi puts it, the strategy of dynamical collapse theories such as GRW's is "to modify the Schrödinger equation, so that superpositions of different 'everyday' states do not arise or are very unstable." (Bacciagaluppi 2012) Hence, according to

[18] cf. Allori 2013, p. 69

Ghirardi, GRW's dynamics guarantee that the quantum wave function will always accurately describe all physical systems[19] at all times:

> "The nice fact is that the resulting theory is capable, on the basis of a single dynamics which is assumed to govern all natural processes, to account at the same time for all well-established facts about microscopic systems as described by the standard theory as well as for the so-called postulate of wave packet reduction (WPR)." (Ghirardi 2011)

To bring it back to the double-slit experiment, GRW ensures that there is no measurement problem in this context, because the laws of the theory entail that "a superposition of 'a counter which has fired' and 'one which has not fired' is dynamically forbidden." (Ghirardi 2011)

Crucially, concepts such as measurement, observation, consciousness, and so on are not playing a fundamental role in the formulation of the theory (as they were in orthodox quantum mechanics)—definite measurement outcomes are derived from the physical dynamics alone. According to GRW's theory, individual quantum entities really do exist in superposition states which rarely collapse; however collections of these entities tend to reach some 'classical limit', spike in amplitude, and then rapidly collapse via a process of 'spontaneous localization' onto localized states "of the form used to describe approximate position measurements." (Bacciagaluppi 2012) On this theory "the overall frequency for collapse is … tied to mass density" (Bacciagaluppi 2012) or in other words a physical system's size or complexity. More specifically: the "spontaneous localization mechanism is enhanced by increasing the number of particles" (Ghirardi 2011) due to the "trigger mechanism" (Ghirardi 2011) known as 'hitting' which is enhanced—referring to the relative effectivity of collapse mechanism going from the micro- to the macro-level—when there are more

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[19] Indeed, according to GRW's "ontologically monistic theory" (Maudlin 2010, p. 122) the wave function representation constitutes a "complete description of reality" (Ney 2013a, p. 34).

particles because the “hitting frequency is … effectively amplified proportionally to the number of constituents.” (Ghirardi 2011) So when the state of a single particle is spontaneously localized, a multiplicative ‘hitting’ process often leads to the suppression of macroscopic superposition because “if any of the particles … undergoes a hitting process … the multiplication prescription leads practically to the suppression” (Ghirardi 2011) of other terms in superposed wave functions not describing the observed measurement outcome. In summary: when there are a large number of particles “any spontaneous localization of any of the constituents amounts to a localization of the [entire system]” (Ghirardi 2011) insofar as the ‘hittings’ invariably amplify to a large number of constituents of the physical system. Thus, although the probability for a single, constituent particle of a physical system to spontaneously collapse is extremely low (securing standard quantum behaviour), by the time you get to physical systems the size of, say, measuring devices, the probability for at least one of their constituents to collapse and ground a definite reality for the overall system through the ‘hitting’ process is extremely high.[20]

According to Ghirardi “the mass density at any point, directly identified by the [wave function] … is the appropriate quantity on which to base an appropriate ontology” (Ghirardi 2011) for this theory. Ghirardi refers to this view as the ‘mass density ontology’:

> “Accordingly … what the theory is about, what is real ‘out there’ at a given space point x, is just a field, i.e., a variable m(x,t) given by the expectation value of the mass density operator M(x) at x obtained by multiplying the mass of any kind of particle times the number density operator for the considered type of particle and summing over all possible types of particles which can be present….[I]f one considers only the states allowed by the dynamics one can give a description of the world in terms of m(x,t), i.e., one recovers a physically meaningful account of

[20] “[A] microscopic system undergoes a localization, on average, every hundred million years, while a macroscopic one undergoes a localization every 10−7 seconds.” (Ghirardi 2011)

> physical reality in the usual 3-dimensional space and time." (Ghirardi 2011)

Thus the manifest image is secured via identifying the continuous distribution of mass throughout ordinary spacetime—where mass density at a single point in spacetime is a function of the dynamics of the wave function (Callender 2009)—with the world of everyday experience made up of tables, cats, and stars and so on.

A very important fact to note (a fact which we mentioned in the introduction) is that collapse theories can be put to the test—if not always in practice, at least in principle—insofar as they "give precise hints about where to look in order to put into evidence, experimentally, possible violations of the superposition principle." (Ghirardi 2011) For example, according to Ghirardi:

> "[Spontaneous localization] being precisely formulated, allows one to locate precisely the 'split' between micro and macro, reversible and irreversible, quantum and classical. The transition between the two types of 'regimes' is governed by the number of particles which are well localized at positions further apart than 10−5 cm in the two states whose coherence is going to be dynamically suppressed." (Ghirardi 2011)

Such experiments would place an upper bound on the size and time scales at which physical systems can be in superposition states, and thus also non-arbitrary limits on collapse models such as GRW's; in order to falsify particular collapse models, all you have to do is experimentally demonstrate maintenance of, for example, quantum superposition states at some size limit where they are posited by such models not to persist.[21]

[21] Interestingly, Maximilian Schlosshauer, Johannes Kofler, and Anton Zeilinger, in 'A Snapshot of Foundational Attitudes Toward Quantum Mechanics', surveyed 33 physicists at a conference dedicated to the foundations of quantum mechanics, and found that exactly two thirds (67%) of respondents replied that they thought that "[s]uperpositions of macroscopically distinct states" are "in principle possible" (Schlosshauer, Kofler, Zeilinger 2013, p. 10).

The theoretical ramifications of such experiments in general were explored by Anthony Leggett and Anupam Garg in 1985, in a paper entitled 'Quantum Mechanics Versus Macroscopic Realism: Is the Flux There When Nobody Looks?' In this paper Leggett and Garg theorize that so-called 'macrorealistic' alternatives to quantum mechanics are inconsistent with—apparently theoretical at the time[22]—observations in macroscopic 'coherence' (i.e. interference / superposition) experiments. Macrorealism or 'macroscopic realism' is the assumption that, past a certain macroscopic limit, objects' properties are always definite (practically speaking, classical), as seems to be required by collapse models. The assumption of macrorealism which is a prior, enabling condition of such models would be falsified if a macroscopic coherence experiment was successfully performed (Leggett and Garg 1985). In a recent discussion about how experimental physics is finally able to put macrorealism to the test, the physicist George C. Knee says the following:

> "Almost a century after the quantum revolution in science, it's perhaps surprising that physicists are still trying to prove the existence of superpositions. The real motivation lies in the future of theoretical physics. Fledgling theories of macrorealism may well form the basis of the next generation "upgrade" to quantum theory by setting the scale of the quantum-classical boundary. … [W]e can be sure that the boundary cannot lie below the scale at which the cesium atom has been shown to behave like a wave. How high is this scale? A theoretical measure of macroscopicity … gives the cesium atom a modest ranking of 6.8 … far below where most suspect the boundary lies. … In fact, matter-wave interferometry experiments have already shown interference fringes with Buckminsterfullerene molecules, boasting a rating as high as 12. … The next step is to try these experiments with atoms of larger mass, superposed over longer time scales and separated by greater distances. This will push the envelope of macroscopicity further and reveal yet more

[22] Perhaps not wholly accurate. As Bacciagaluppi points out, as far back as 1984 states of superposition were observed in the "macroscopic currents" (Bacciagaluppi 2012) of SQUIDS (which are superconducting devices).

> about the nature of the relationship between the quantum and the macroworld.” (Knee 2015, p. 2)

As a preliminary example of how physics might finally able to reveal much about the nature of the relationship between the quantum and macroscopic worlds, the physicists Roohollah Ghobadi et. al. argue that experiments which generate states of superposition in macroscopic physical systems constitute direct tests of collapse theories (which assume macrorealism) insofar as one can utilise their results to see whether such superposition states persist on time-scales longer than that at which collapse is postulated to take place, for example, on the order of micro-seconds. Further, they argue that such experiments are realisable with current technology (Ghobadi, Kumar, Pepper, Bouwmeester, Lvovsky, Simon 2014). Similarly, the physicists Dustin Kleckner et. al. propose an experiment which would establish a lower-bound on the ‘nonclassicality’ of ‘relatively massive’ or macroscopic objects. They argue that the time-scale of collapse mechanisms such as those which invoke gravitational collapse means that if gravity collapses the wave functions of macroscopic objects then superpositions will not be realized over the proposed time-scale of their experiment (Kleckner, Pikovski, Jeffrey, Ament, Eliel, Brink and Bouwmeester 2008).

More practically: in 2002 a group of experimental physicists led by Anton Zeilinger demonstrated interference with buckyballs (fullerene C70) which are macromolecules made up of 70 carbon atoms, which is an order of magnitude larger than entities traditionally thought be be solely quantum such as photons and electrons (Brezger, Hackermüller, Uttenthaler, Petschinka, Arndt, and Zeilinger, 2002). Likewise, in 2013 interference was demonstrated with an entire molecule made up of 810 atoms (made up of around 5000 protons, 5000 neutrons, and 5000 electrons) called C284.H190.F320.N4.S12. Allegedly, systems of this complexity are approaching the size of some primitive viruses

(Eibenberger, Gerlich, Arndt, Mayor, Tüxen 2013). On that point, other researchers speculate that—technical difficulties aside—quantum interference experiments can in principle be set up in order to test for quantum superposition in entities as complex as micro-organisms such as the flu virus (Romero-Isart, Juan, Quidant and Cirac 2010).

Perhaps most definitively: in 2010 a group of experimental physicists put a metal paddle *visible to the naked eye* (30 micrometres across) into a superposition state. Once they got over the technical problem[23] of figuring out how to reliably get a mechanical entity into its 'ground state' (i.e. the state of lowest energy permitted to it by the laws of quantum mechanics), the team were able to cool the metal paddle until it reached this ground state, and then connected it to a bona-fide quantum superconducting current which was prepared in a superposition of 'pushing' and 'not pushing' simultaneously; once connected, the physicists were able to detect the paddle (which was made up of *trillions* of atoms) in a superposition state of vibrating and not vibrating at the same time (O'Connell et al. 2010).

Lev Vaidman, in his discussion of similar results, argues that the burden of proof ultimately lies with the *proponents* rather than opponents of collapse theories, insofar as it is they who posit "new physics beyond the well-tested Schrodinger equation." (Vaidman 2014) He makes the point that any observable phenomena predicted by such models have simply not been detected experimentally (up to the level of complexity which experimental physicists are able to probe, given current technical limitations) and cites this situation as a

[23] The idea of testing quantum mechanics's application to macroscopic physical systems has been hindered mostly by practical, rather than theoretical, problems. See e.g.: "[A] demonstration that quantum mechanics applies equally to macroscopic mechanical systems has been a long-standing challenge, hindered by the difficulty of cooling a mechanical mode to its quantum ground state. The temperatures required are typically far below those attainable with standard cryogenic methods, so significant effort has been devoted to developing alternative cooling techniques." (O'Connell et. al. 2010, abstract)

lack of evidence for any new physics beyond the deterministic, linear Schrodinger dynamics, although he concedes that this merely means that “some (but not all!) of these [collapse] models have been ruled out” (Vaidman 2014). What he means by this is that, although such experiments do not definitively rule out *all* collapse theories, they at least place quantifiable restrictions on the bounds within which such models can justifiably determine collapse to take place (Vaidman 2014). Yet, as I have hopefully made clear, these bounds are shrinking all the time and in fact the laws of quantum mechanics have arguably been shown to apply to bona fide macroscopic systems (most plausibly the metal paddle which was put into a superposition state).

Although obviously not definitive for all time, the empirical data wrested from the macroscopic superposition experiments discussed in this section nevertheless suggest that there is currently no empirical evidence for a physical process that causes wave functions to ‘collapse’ via, for example, spontaneous localization or the effects of gravity at some macroscopic limit. Specifically, at the present moment it appears that there is no exactly-quantifiable macroscopic limit one can point to and say that is where linear evolution fails and some sort of ‘collapse’ process kicks in and determines the evolution of physical systems instead. Because of this, at the present time there appears to be no conceptual barrier in principle to the idea of extending quantum mechanics to the macroscopic scale wholesale.

As a suggestion of what the breakdown of this conceptual barrier entails, we will take a detour through Erwin Schrodinger’s ‘Schrodinger’s cat’ thought experiment, through which he sought to demonstrate what he saw as the obvious and latent absurdity in taking the wave function evolving according to the Schrodinger equation as an accurate and complete representation of all (i.e.

microscopic *and* macroscopic) physical systems. In particular, Schrodinger wanted to probe whether sense could ultimately be made of regarding a macroscopic physical system (in this case, a cat) as being in a superposition of macroscopically distinct states—both alive and dead—at the same time.[24] Schrodinger started by positing an imaginary physical set-up made up of a cat in a box containing a vial of lethal gas which would either release or not release depending on the outcome of a bona fide quantum event: nuclear decay. He argued that the state of superposition would transfer from the microscopic nucleus (which, per the quantum laws, would both decay and not decay) to the vial of lethal gas (which subsequently would both release and not release) and ultimately to the cat via the process of entanglement, whereupon the cat would evolve into a superposition of being both alive and dead at the same time, insofar as the uninterrupted linear evolution of the Schrodinger dynamics would preserve superpositions. Many since have taken Schrodinger's argument to definitively demonstrate the absurdity of extending the laws of quantum mechanics from the microscopic to the macroscopic realm.

And yet in 2013 a group of physicists demonstrated entanglement between microscopic and macroscopic physical systems when they detected microscopic quantum fluctuations in a photon exhibiting strong quantum correlations (i.e. entanglement) with macroscopic fluctuations in a group of 100 million photons (Lvovsky, Ghobadi, Chandra, Prasad and Simon 2013). In their discussion of this result, they write:

> "Although Schrödinger's thought experiment was originally intended to convey the absurdity of applying quantum mechanics to macroscopic

[24] Or perhaps for Schrodinger only until it is observed. As per the the orthodox interpretation of Schrodinger's day, the cat would only exist in a superposition state of *both* alive *and* dead until it was observed on which its wave function would collapse to a definite *either* alive *or* dead state. Nevertheless for Schrodinger the prediction that the cat would exist in a superposition of macroscopically distinct states *before* measurement was absurd enough in itself to warrant his suspicion about extending the laws of quantum mechanics beyond the microscopic level.

> objects, this experiment and related ones suggest that it may apply on all scales." (Lvovsky, Ghobadi, Chandra, Prasad and Simon 2013, p. 541)

If the laws of quantum mechanics apply on all scales then the linear dynamics are not confined solely to the microscopic level of reality and macroscopic systems can also be considered to be described by a wave function which obeys the Schrodinger evolution (that is, prior to measurement, at least; remember that we still haven't really 'solved' the measurement problem). What would a theory which takes such claims seriously entail about the nature of reality in a general sense?

3.2: Unitary quantum mechanics

Insofar as recent experiments suggest that there is currently no empirical evidence for a process of collapse (i.e. von Neumann's Process 1), and furthermore that entanglement can transfer between microscopic and macroscopic physical systems, then solving the equations of motion for such a theory returns this result where the linear dynamics *always* determine the evolutions that *all* physical systems undergo (Ney 2013b, p. 170). Accordingly everything, including macroscopic physical systems, can be represented by a wave function obeying the Schrodinger equation. That is, on such a theory, quantum dynamics are *unitary* (Zurek 2010, p. 416) and there is no quantum-classical boundary. Since the same laws apply at every level, macroscopic physical systems such as measuring devices etc. can become entangled with superposed entities such as photons and evolve into superposition states themselves (insofar as entanglement is a process which amplifies microsuperposition to macrosuperposition). Take this line of thought to its logical conclusion, and it's perfectly clear what the quantum algorithm predicts in general: measuring devices (including the brains of observers) will always be sensitive to all the amplitudes of the wave function and really should register superpositions of all possible measurement outcomes.

However, observers' experiences aren't anything like that when they run quantum experiments; for example, device readouts are never observed to display *both* up *and* down at the same time—observers always experience definite measurement outcomes instead. The problem with unitary quantum mechanics is thus the problem of working out how a quantum theory which describes all physical systems at all times could ever correspond to the manifest definiteness of observers' experiences: how could entangling interactions between superposed entities ever yield definite measurement outcomes? Thus we're led straight back to the measurement problem, this time in the guise of the 'macroscopic superposition problem' (although they are essentially the same thing), succinctly described by Valia Allori:

> "[I]f the wave function completely describes physical systems, and it evolves according to the Schrödinger equation, then … macroscopic superpositions that we clearly never observe … are produced." (Allori 2013, pp. 66-67)

The problem of macroscopic superposition is thus the problem of accounting for what it could mean for there to be superpositions of distinct states for macroscopic physical systems as the unitary dynamics predicts (Ghirardi 2011). Essentially, we are brought right back to the perplexing question of why, given all the undeniable successes of quantum theory, it also predicts physical states that are manifestly never observed. How do you make sense of the idea of macroscopic objects in states of superposition when it always seems that their wave functions collapse onto definite measurement outcomes when they are observed? Why, if the dynamics are linear and unitary, does the macroscopic world *appear* classical? (Faye 2014) Put simply: whence the manifest image?

According to Jim Hartle, questions surrounding the problem of macroscopic superposition form a “key part of the general question of the emergence of classical behaviour from quantum theory” (Hartle 2010, p. 99) in general. This question essentially concerns the task of grounding the connections between appearance and reality i.e. the manifest and scientific images of nature, which—if you’ll think back to the introduction—just happens to be the question this essay is invested in exploring. In order to adequately solve this problem, you at least need a physically-sensible theory which coheres with the all the available experimental data. Yet, being empirically-inadequate, collapse approaches are out of the picture. So we had better try to find a better interpretation.

3.2.2: Pure wave mechanics

Hugh Everett III developed his ‘pure wave mechanics’ primarily in response to conceptual difficulties thrown up by the collapse postulate.[25] Everett sought an interpretation which eliminated the collapse postulate from the orthodox quantum dynamics, and yet nevertheless provides a complete physical theory insofar as the wave function always evolving via the Schrodinger dynamics accurately and completely describes all physical systems at all times. The main interpretational task of Everett’s pure wave mechanics is thus to explain observers’ experiences of definite measurement outcomes (i.e. the appearance of a single manifest world) without reference to some arbitrary collapse process which breaks the linear dynamics. Everettians simply dis-solve[26] the measurement problem by rejecting the assumption that definite measurement

[25] For example the facts that collapse is “indeterministic and non-linear, respecting none of the spacetime or dynamical symmetries” (Saunders 2010, p. 3).

[26] That is, proponents of such theories claim that quantum mechanics provides its own interpretation or that quantum mechanics should be interpreted literally when it describes superpositions of measurement outcomes (Faye 2014), and that pure wave mechanics is merely the result of such an attitude.

outcomes capture the true nature of reality (Faye 2014). Instead they argue that macroscopically distinct states of superposition can be considered meaningful after all (Bacciagaluppi 2012).

Pure wave mechanics ultimately attempts to square orthodox quantum mechanics's empirical virtues (such as the *appearance* of collapse) with what the unitary quantum dynamics predict by recapturing observers'[27] experiences in terms of "determinate relative measurement records" (Barrett 2014). Central to Everett's solution to the measurement problem is the distinction between the absolute state and relative states of physical systems (Barrett 2014), from which he derives his principle of the 'fundamental relativity of states' (Everett 1956, p. 103). This is the principle that subsystems of a composite physical system's states are not independent from the states of the rest of the system because the subsystems' states are correlated (entangled) with eachother (Barrett 2014). Thus, according to Everett:

> "It is meaningless to ask the absolute state of a subsystem—one can only ask the state relative to a given state of the remainder of the subsystem." (Everett 1956, p. 103)

Taking Everett's principle of the fundamental relativity of states on board, if you consider the *absolute* state of a physical system, then there are no definite measurement outcomes; however if you consider the *relative* states of a physical system, there are definite measurement outcomes (Barrett 2014). For example, consider a composite physical system made up of an observer, a measuring device, and a photon, which are each its subsystems. Measurement understood as entangling interaction entails that the measuring device, on measuring the photon, evolves into a state of entangled superposition; likewise

[27] Where 'observers' are themselves considered physical systems, made of particles, and thus subject to the laws of quantum mechanics.

the observer, on observing the readout on the measuring device, evolves into a superposition of experiencing all possible states of the device. The *absolute* state of the composite system is thus indefinite, while each of its terms are in definite, *relative* states, corresponding to 'eigenstates' of the observed variable (Barrett 2014). Thus on Everett's interpretation, each term in the entangled superposition explicitly represents a different observer experiencing a definite measurement outcome.

A number of questions may be raised at this point regarding the "empirical faithfulness" (Barrett 2014) of the Everett interpretation, which may appear radically discontinuous with experience at first glance. One question concerns the extra structure corresponding to the 'branches' of the absolute wave function that observers don't experience; along with the question of why observers don't experience these other branches.[28] A directly-related question concerns how to pinpoint experience in this theory. For example, Craig Callender asks where, in the structure of the wave function, does an observer's experience of definite measurement outcomes supervene? (Callender 2009). Addressing these problems will be instructive in further elaborating the empirical consistency between Everett's conception of reality and the manifest world that we all experience.

To take the second question first: Everett states that in order to be empirically acceptable, a scientific theory need not be isomorphic to experience; rather it is enough to find a homomorphism (a structure-preserving representation) between the theory and experience instead (Barrett 2014). Everett then pinpoints observers' experiences of definite measurement outcomes in their 'relative memory records'. What Everett means by this explanation is to suggest

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[28] The wave function of a macroscopic physical system in a superposition of macroscopically distinct states have peaking amplitudes which are well-separated in configuration space; these amplitudes may be described as 'branches'.

that definite outcomes are represented by specifying a decomposition of the absolute state which correlates a measurement outcome with the corresponding relative memory record. So given the linearity of the Schrodinger dynamics, after measurement every possible outcome will be represented in the entangled superposition state as a sequent in a sequence of relative measurement outcomes (which includes an observer's memory records). Thus, in the absolute state of a composite physical system, the terms of the superposition correspond to different relative measurement outcomes; all possible outcomes can each be specified by a relative memory record so an observer's experience is always able to be pinpointed by specifying such a record which is homomorphic to it (Barrett 2014).

The question regarding why observers don't experience these other branches of the wave function was also partly addressed by Everett when he stated that while which outcome an observer experiences is a *relative* fact, that it seems to an observer that they experience a definite outcome is an *absolute* fact (Barrett 2014). This entails that it will always *seem* to an observer that they experience a definite measurement outcome, when, in reality, they experience every possible outcome (Barrett 2014). So although the objective, outside, or 'bird's eye' (Tegmark 2008) perspective of the wave function represents a multiplicity of all possible measurement outcomes taking place, from the subjective, inside, or 'frog's eye' (Tegmark 2008) perspective only definite measurement outcomes are observed. This is arguably due to the process of 'environmental decoherence', which, although not known in its full details by Everett himself, gives legs to his explanation of why the other branches of the wave function aren't experienced. The short explanation is that decoherence—as suppression of coherence i.e. superposition—means that interference between terms in the wave function describing distinct histories almost instantaneously vanishes at the macroscopic scale.[29] Decoherence causes the interference term in wave functions (responsible for superposition) to be suppressed not as a result of measurement, but rather as a result of a physical system's interaction with its environment (Bacciagaluppi 2012). Because decoherence suppresses interference in very short orders of time, at very small spatial magnitudes, this makes macroscopic branching practically impossible to experience, since experience takes place at a far more coarse temporal grain than the one that is subject to decoherence (Bacciagaluppi 2012).

In the philosophy and physics literature, the 'branches' of the wave function are often casually referred to as 'worlds' outright. However 'worlds' are not precisely delineated entities in the underlying struture of Everett's original formulation of pure wave mechanics. This is because, according to David Wallace, 'worlds' are typically construed as temporally-extended structures, so identity over time is a necessary condition for identifying them, and yet there is an arbitrary amount of ways to decompose the wave function into mutually orthogonal states due to Everett's original principle of the relativity of states which allows for arbitrary decompositions of the absolute state of a physical system into any basis (Barrett 2014). This follows from Everett's operationalism[30] which leads him to take all branches in all bases as real, insofar as the linearity of the Schrodinger dynamics requires pure wave mechanics to assign reality to every relative state because all branches of the wave function always have the potentiality to interact with eachother, meaning that all branches in all bases have potential empirical consequences (Barrett 2014). Taking Everettian branches to explicitly represent worlds thus requires specifying some 'preferred basis' from which they can exhibit diachronic identity. David Wallace points out that decoherence itself selects such a basis because it specifies a set of preferred variables and

[29] For what it's worth Zurek 1998 and Zeh 2000 suggest that decoherence incorporates itself most naturally with Everettian interpretations (Bacciagaluppi 2012).
[30] Operationalism is an epistemic stance which takes anything that has potential empirical or observational consequences to be real (Barrett 2014).

enables reidentification of these states over time. This is because decoherence happens when the environment of a system under scrutiny—e.g. “stray particles” in the system’s environment (Bacciagaluppi 2012)—entangles itself with that system, causing the environment to continually ‘observe’ or ‘measure’ some preferred variable of the system, making these ‘preferred states’ relatively stable in the process. Because interaction potentials are generally a function of position, the set of preferred variables is mostly related to the ‘classical observables’ position and, given the indeterminacy relations, momentum (Bacciagaluppi 2012). Environmental interactions then privilege ‘measuring’ some approximate position or momentum eigenstates, as a general rule. The preferred states of these classical observables are made ‘robust’[31] via a process called ‘superselection’ which happens when information about a physical system is lost to and then stored in the environment (Bacciagaluppi 2012).

A consequence of this is that ‘worlds’ can be defined as, e.g., the “decoherent histories” (Wallace 2010) of such states.[32] Following Wallace I will define ‘worlds’ as temporally-extended histories that ‘branch’ from the wave function via a process of decoherence which also grounds their stability.[33] This explanation has the consequence that there is no ‘problem of preferred basis’ because specifying such a basis need not be an additional, arbitrary postulate: such a structure emerges naturally from the decoherent dynamics of the wave function in-itself (Bacciagaluppi 2012). Understood in this way, every term or

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[31] Robustness in this context just means that because the relevant information is being stored in the system’s environment, an ‘observer’ can reliably pick up this information directly from the environment, without further disturbing the system (Bacciagaluppi 2012).

[32] Another way of putting it is that decoherence causes branches of the wave function to “dynamically isolate” themselves from one another (Saunders 2010, pp. 4-5) and “it is the dynamical isolation of these branches that makes them Everett worlds” (Ladyman 2010, p. 157). This is because dynamical isolation enables the formal reidentification of wave trajectories over time (Bacciagaluppi 2012) and thus grounds a diachronic identity for ‘worlds’ as stable, dynamically-separated ‘branches’ of the wave function (Saunders 2010, p. 5).

[33] Of course, according to Wallace the concept of ‘splitting’ is only approximate i.e. FAPP (for all practical purposes). Nevertheless the theory is empirically-adequate insofar as it grounds experience and gets the correct predictions for quantum experiments (Wallace 2010).

amplitude in the wave function which represents a distinct measurement outcome represents a stable ‘branch’ and therefore a ‘world’ (Allori 2013, p. 69): hence why this interpretation is popularly known as ‘Many-Worlds’. These worlds are differentiated from eachother by virtue of having at least one physical system in a different microphysical state.[34]

So to summarise how pure wave mechanics deals with the measurement problem: if the state of something (such as the readout of a measuring device) interacts with something else (such as the state of a photon), then those two things can become correlated, and thus entangled. Measuring devices tend to become entangled with their environments (stuff extraneous to the physical system under scrutiny) to such an extent that the amplitudes of their wave functions can no longer interfere due to coherent information constantly being lost to the environment: when measurement (as a form of entangling interaction) decoheres the wave functions of superposed quantum systems, this means that coherent information is lost to the environment and their amplitudes are no longer interfering with eachother. Yet the amplitudes of the wave function are required to be precisely aligned in order to exhibit interference. Hence why interference effects (and thus superpositions of measurement outcomes, etc.) are never able to be observed or measured at the macroscopic level.

Furthermore, the possible physical configurations that these amplitudes represent can thus be regarded for all practical purposes as their own worlds insofar as they evolve approximately independently from eachother into their own branches of the wave function. Accordingly, for pure wave mechanics Schrodinger’s cat really *is* dead and alive at the same time and, furthermore, if a physicist decides to measure the state of the cat, then this corresponds to a

[34] In more technical terms: if worlds are differentiated by virtue of having at least one object in a different state, this means that different states are orthogonal to eachother (because orthogonality entails possessing different eigenvalues), such that ‘worlds’ can be defined as mutually orthogonal states (Barrett 2014).

situation where there really are multiple observers, each of whom experiences a distinct, definite state of the cat (Wilson 2013, p. 583).

Insofar as interference is a paradigmatically quantum phenomenon, decoherence, which causes physical systems to exhibit “negligible interference” (Halliwell 2010, p. 99) leads to approximately classical behaviour.[35] That is, if you take decoherence into account, you can treat a quantum event (such as a photon landing on a screen) as a consequence of an individual component of a wave function (*either* the photon travelled through the left slit, *or* it travelled through the right slit), rather than having to treat each and every component of the wave function interfering with eachother as contributing to the final outcome (Bacciagaluppi 2012). More generally, the probabilities for measurement outcomes can be treated classically, ‘as if’ the wave function has ‘collapsed’ to a definite value. Decoherence thus secures the *appearance* of collapse in a phenomenological sense (Bacciagaluppi 2012). This likewise allows one to recover a ‘quasiclassical’ dynamics, for example, approximately Newtonian trajectories, and so on (Bacciagaluppi 2012).[36]

[35] Incidentally, decoherence is one of the technical reasons why superposition experiments with macroscopic physical systems have not been able to be performed until relatively recently. This is because decoherence places limits on physicists’ ability to preserve quantum properties such as interference at the macroscopic scale: sensitivity to environmental interaction grows exponentially with the size of the physical system involved, due to the increasing likelihood of one of the system’s particles being disturbed by, for example, stray particles in its environment and becoming entangled with it, which leads rapidly to loss of coherence (this is the reason why quantum computers must be shielded from decoherence also). See e.g. Sadegh Raeisi, Pavel Sekatski, and Christoph Simon 2011 where they argue that the possibility of directly measuring the presence of micro-macro entanglement of superposition approaches 0 as system complexity (size) increases; most states of macroscopic superposition can therefore only be inferred indirectly from interference experiments, for example. However recent advances in technology allowing such physical systems to be ‘shielded’ from decoherence have made many such experiments feasible.

[36] This point has been generalized in a result known as Ehrenfest’s theorem, which states that since the ‘preferred states’ picked out by decoherence are generally wave functions localized in position (i.e. ‘wave packets’). These localized wave packets’ dynamics can then be treated as approximately Newtonian (Bacciagaluppi 2012).

According to Hartle, decoherence likewise implies coarse-grained classical behaviour “well above the Planck scale” (Hartle 2010, pp. 92-93) due to following conservation laws such as the “conservation of energy and momentum” (Hartle 2010, pp. 92-93). This is because decoherence is a process that separates the variables describing a physical system into ‘fast’ and ‘slow’ (Halliwell 2010, pp. 99-100). The ‘slow’ variables of a physical system are its “local densities” (Halliwell 2010, pp. 99-100) which obey conservation laws; these conserved densities allow a physical system which is described by quantum mechanics at the microscopic level to be described classically at the macroscopic level, insofar as “exactly conserved quantities obey superselection rules” (Halliwell 2010, pp. 99-100) which preserve “local density eigenstates” in “time evolution”, causing them to “behave quasiclassically” (Halliwell 2010, p. 114).

Decoherence thus arguably grounds the connection between the manifest image of experience from the scientific image of quantum mechanics more generally. On this view, the manifest image corresponds to some ‘quasiclassical realm’ that reduces to a decoherent history of the wave function. The relationship between the “quasiclassical realms” (Hartle 2010) of everyday experience and the image of the world implied by quantum mechanics is argued by Hartle to be “top-down—proceeding from the classical world to the quantum” (Hartle 2010, p. 92). Likewise, Ladyman notes that “[t]he physics of decoherence is a top-down reduction.” (Ladyman 2010, p. 157) That is, given a pre-supposed description, in terms of the higher-level concepts of classical physics, of the manifest image of everyday macroscopic objects such as chairs, cats, and stars, decoherence gives you the resources to successfully reduce this image to the scientific image of quantum mechanics:

> "[T]he macroworld is recovered only as a coarse-grained feature of the microscopic world not as a precise and definite entity in its own right." (Ladyman 2010, p. 158)

According to this view, quantum systems exhibit classical behaviour when their histories for motion exhibit a 'coarse-graining' that singles out variables whose values are averages of conserved quantities; furthermore these are what "define quasiclassical realms" (Hartle 2010, pp. 92-93) insofar as their evolution can be approximately described by classical laws. Within such decoherent histories there needs to be some variables you can identify with familiar macroscopic objects; these variables are given by the densities of conserved quantities which are stable in time evolution in order to satisfy typical descriptions of classical behaviour:

> "The familiar quasiclassical domain is characterized by local densities obeying closed sets of deterministic evolution equations. This domain may also be referred to as a reduced description of the quantum system" (Halliwell 2010, p. 114).

Everett states that pure wave mechanics allows one to understand reality both as "objectively continuous and causal, while subjectively discontinuous and probabilistic" (Everett 1956, p. 78).[37] Thus Everett's interpretation arguably allows one to understand quantum mechanics as a theory which the captures the most important aspects of the scientific and manifest images of nature, respectively.

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[37] To take a simplified model: if you have a radioactive element with a half-life of, say, an hour, and which is subject to quantum laws, such that, on average, half of it will have decayed after an hour is up, then there is no way of predicting which of it will decay, no matter how complete your knowledge of the overall system. This is because since all measurement outcomes occur, you would have to be able to predict which branch of the wave function you 'end up in', but since you really you end up in them all, this would be impossible to do. Hence the subjective stochasticity in the face of objective determinism.

Proponents of Everett’s interpretation argue that it is the ‘pure’ interpretation of quantum mechanics insofar as it posits no additional structure beyond the wave function and the Schrodinger equation which determines its evolution: these ‘many worlds’ emerge solely from the physical formalism of the universal wave function evolving deterministically according to the Schrodinger equation. A consequence of this is that, if a physical process of, say, spontaneous localization or gravitational collapse is ever verified at some definite macroscopic limit, then this phenomenon would constitute a direct refutation of pure wave mechanics. Conversely, experimental demonstration of macroscopic objects exhibiting interference effects should be regarded as constituting empirical evidence for the truth of pure wave mechanics. Indeed, according to Jeffrey Barrett, “*any* experiment that illustrates quantum interference provides empirical evidence for the operational existence of alternative … branches” (Barrett 2014, emphasis added). The upshot is that, at the present moment in time at least, the available empirical evidence suggests the reality of macroscopic superposition (and so the existence of ‘many worlds’), as opposed to some definite reality.[38]

Nevertheless many people are deeply unsettled by pure wave mechanics insofar as it entails that anything that can happen, does happen, in a different world (Allori 2013, p. 69). This is because the dynamics of pure wave mechanics predict that the wave function of the universe evolves through every single one of its possible states. So here we have a theory which does violence to most people’s a priori criterion of sensibility, insofar as it doesn’t take much power of imagination to realise that pure wave mechanics leads to absurd consequences (within the realms of physical possibility)—in fact potentially an infinity of them! For example, the dynamics of pure wave mechanics entail that a future ‘you’ will necessarily evolve into a world where you will, to take a

[38] cf. the discussion of the empirical (dis)confirmation of quantum phenomena such as superposition at the macroscopic level in the section on dynamical collapse theories.

suggestive example, walk into your kitchen to find an elephant standing there (or more likely a baby elephant if your kitchen is small). That's the 'elephant in the room' for pure wave mechanics, so to speak. A physical theory should at least be sensible, but it is hard to make sense of a theory that can in principle predict everything—including the most absurd things.

3.3: Hidden variables

Albert Einstein, too, was deeply unsettled by many of quantum mechanics's implications (such as its apparent incompatibility with Special Relativity), and due to this disconcertment wanted to figure out whether "the wave function [gives] us an ontologically complete representation of a system at a time" (Ney 2013a, p. 19). Einstein realised that if the wave function was proved to be an incorrect or at least incomplete description of reality, then this would nullify many of quantum mechanics's implications that he found distasteful and so to that end, he, along with the physicists Boris Podolsky and Nathan Rosen (EPR), devised a thought experiment designed to show that the wave function representation is incomplete. EPR argued that if the wave function does not represent the complete reality of physical systems, then some 'hidden variables' [39] must be posited alongside it in order to form a deeper, more complete physical theory from which quantum phenomena emerge as "equilibrium statistical effects" (Bacciagaluppi 2012). According to these so-called 'hidden variables' theories, the real ontology of quantum mechanics is 'hidden', i.e. not captured within the description given by the wave function on its own. These hidden variables constitute the 'primary' (Maudlin 2013) or 'primitive' (Allori 2013) ontology of quantum mechanics, i.e. what the macro-objects in the ordinary world of experience are *really* made up of (Saunders 2010, pp. 4-5).

[39] Some sort of additional parameters or equations not contained within the wave function description (Saunders 2010, p. 4-5).

In fact, strictly speaking, hidden variables theories are not even really 'interpretations' of quantum mechanics in the strict sense; insofar as they posit a different ontology and dynamics they are in fact different—although empirically-equivalent[40]—theories altogether.

The EPR argument goes (roughly[41]) as follows: EPR point out that quantum mechanics entails that it is impossible to predict with certainty what the value of a variable will be prior to measurement, since the wave functions of physical systems only give you the *probabilities* for measurement outcomes on those systems. Furthermore, they point out that if a measurement is performed on a particle in an entangled physical system, knowledge of the state of the other particle is thereby gained without having to perform a measurement on it, because, as an element in an entangled system, its spin (for example) can be known to be necessarily anti-correlated with the value of the other particle's spin (Krips 2007). This fact is seen if you consider a version of EPR's thought experiment developed by the physicist David Bohm (EPRB). In the EPRB experiment, a pair of electrons are prepared in the state of entangled spin known as the singlet state (Ney 2013a, p. 19)

$$\psi_{\text{singlet}} = \sqrt[1]{2}\ |\text{x-spin up}>_1\ \sqrt[1]{2}\ |\text{x-spin down}>_2 + \sqrt[1]{2}\ |\text{x-spin down}>_1\ \sqrt[1]{2}\ |\text{x-spin up}>_2$$

Bohm argues that the singlet state spin correlations mirror the standard EPR correlations, and so the measured spin-values are known to always be negatively correlated (for example if one electron is measured to have a positive spin value, then the other will necessarily be measured to have the opposite

[40] Sheldon Goldstein: "Bohmian mechanics is empirically equivalent to orthodox quantum theory" (Goldstein 2013).

[41] What follows will not be a reconstruction of any particular argument EPR actually gave, but rather a construction of an EPR-style argument more generally.

negative spin value, and vice-versa).[42] That is, because the singlet state is a state of entangled superposition of spin, one cannot have intrinsic knowledge the states of the individual electrons; rather one can only have the correlational knowledge that their spin states are opposite (Ney 2013a, p. 19). After the electrons are prepared in the singlet state, they each fly off into space in different directions, such that they can be considered “out of each other's immediate spheres of influence, so that a disturbance of [one] has no immediate effect upon [the other]” (Krips 2007). This state of affairs entails that if two physicists, Alice and Bob, decide to perform a measurement on one of the electrons, then if Alice’s particle is measured to have a positive spin value +1/2, Bob’s particle will necessarily be measured to have a negative spin value -1/2, and vice-versa.

EPR assume that “when they are spatially separated, some “reality” pertains to both components of the combined system.” (Fine 2013) This is due to the principle of ‘separability’, which they assume outright. Separability is the principle that quantum systems have realities independent from goings on at separate systems: an independent reality pertains to all quantum systems, even when these systems are entangled and thus described by the same wave function (Fine 2013). Likewise, EPR take the principle of ‘locality’ as axiomatic—not surprising given its centrality to Einstein’s theory of Special Relativity. Locality is the principle that “if two systems are far enough apart, the measurement (or absence of measurement) of one system does not directly affect the reality that pertains to the unmeasured system.” (Fine 2013) So for EPR a measurement on one particle in an entangled system can have no instantaneous effect on the state of the other particle, due to the principles separability and locality:

[42] This is due to the law of conservation of angular momentum which entails that total spin angular momentum must always equal zero.

> “In Einstein's arguments the locality principle makes explicit reference to the reality of the unmeasured system (no immediate influence on the reality there due to measurements made elsewhere).” (Fine 2013)

Basically, for EPR the principles of locality and separability ‘decontextualize’ the reality of a quantum system from the reality of a separate system, even if those systems are entangled, such that no changes with respect to what is real can take place in one system as a consequence of a measurement on another (Fine 2013). As Einstein puts it in a letter to Max Born, separability-locality entails that physical systems situated in different parts of space-time maintain an independent existence from eachother:

> “It is … characteristic of … physical objects that they are thought of as arranged in a space-time continuum. An essential aspect of this arrangement … is that they lay claim, at a certain time, to an existence independent of one another, provided these objects “are situated in different parts of space”. … The following idea characterizes the relative independence of objects (A and B) far apart in space: external influence on A has no direct influence on B.” (Einstein 1948)

EPR’s thought experiment suggests that a direct measurement by Alice on her particle constitutes a sort of ‘indirect’ measurement Bob’s particle insofar as this information allows Alice to predict the measurement outcome on Bob’s particle with probability 1 (Fine 2013). However since these systems cannot be interacting (given locality and separability), it yields this information at-a-distance insofar as a measurement performed on one particle in an entangled system seems to instantaneously determine the state of the the other particle, even if the particles are separated by a distance such that no influence could possibly be transmitted between them in the time it takes to run the experiment without explicitly violating the speed-limit placed on information-transfer by his theory of Special Relativity, because the probabilities for measurement outcomes on Bob’s particle given by the wave function (which, per the laws of quantum mechanics, are indefinite prior to measurement) instantaneously change. For example, measurement of the spin of one electron instantly determines the probability—i.e. from 50% to 100% / 0%—of measuring the other electron as having opposite spin. That is, before measurement, each electron has 50% chance of being measured to have x-spin up; however after measurement of the first particle as having x-spin up or down; it is then instantaneously known that the second particle has either 0% or 100% probability of being measured to have x-spin up or x-spin down (Ney 2013a, pp. 19-20). Einstein designated this ‘spooky action at a distance’ because he argued that the instantaneous change in probabilities would have to correlate to some real, nonlocal change in the physical state of the system. Thus according to standard quantum mechanics, entanglement:

> “[M]akes the reality [of the second system] depend upon the process of measurement carried out on the first system, which does not in any way disturb the second system. No reasonable definition of reality could be expected to permit this.” (EPR 1935, p. 780)

Since “[s]eparability supposes that there is a real state of affairs and locality supposes that one cannot influence it immediately by acting at a distance.” (Fine 2013), EPR argue that what their thought experiment shows is that there must be some definite ‘hidden variables’ locally determining the probabilities for measurement outcomes not taken into account by the wave function. EPR establish this by arguing that since locality prohibits instantaneous influence between separate physical systems in a state of entanglement, and because through measurements on one particle in such a system knowledge is thereby gained of the other particle’s variable without having measured it, then due to what they term the ‘Criterion of Reality’, this value must always have been an ‘element’ of its ‘physical reality’:

> "If without in any way disturbing a system we can predict with certainty … the value of a physical quantity, then there exists an element of physical reality corresponding to this physical quantity" (EPR 1935, p. 778).

That is, if you can predict the value of a physical quantity with certainty, then an 'element of reality' corresponds to it. Because for EPR "every element of physical reality must have a counterpart in the physical theory" (Fine 2013), and because wave functions don't contain such counterparts, this means that the wave function is an incomplete representation of reality.

To summarise: if you consider the total wave function for Alice and Bob's entangled electrons (i.e. the singlet state), then, given the assumptions 'locality' and 'separability', the state of Bob's electron cannot depend upon any measurements made on Alice's electron. Due to conservation laws, a measurement by Alice on her electron allows her to instantaneously infer the measurement outcome on Bob's electron with probability 1. Because of this—given the 'Criterion of Reality'—the value of the spin variable on Bob's electron must be considered to correspond to its 'elements of reality', since it can be predicted with certainty without having to go to the bother of directly influencing it. In essence, for EPR these 'elements of reality' are "are further hidden facts about [Alice and Bob's electrons'] individual spins that ensure their states are correlated in the appropriate way" (Ney 2013a, p. 20) in order to ensure that there is nothing nonlocal happening in the context of measurements on Alice and Bob's entangled particles. Yet because the wave function of the combined (Alice + Bob) system does not specify these 'further hidden facts', EPR argue that the wave function representation of quantum mechanics must be considered incomplete (Fine 2013). As Abner Shimony puts it:

> "[I]n order to avoid an appeal to nonlocality these correlations could only be explained by "elements of physical reality" in each particle … and since this description is richer than … Quantum Mechanics their

> conclusion is effectively an argument for a hidden variables interpretation." (Shimony 2009)

'Hidden variables' interpretation more generally are deterministic, no-collapse theories which reject "the assumption that the quantum state is a complete description of reality" and which therefore posit "more variables … than are contained within the quantum state" (Ney 2013a, pp. 29-30).

3.3.3: Bohmian mechanics

The most prominent of hidden variables theories is 'Bohmian mechanics'—also known as de Broglie-Bohm theory—developed by the American physicist David Bohm (building off an earlier hidden variables theory formulated the Italian physicist Louis de Broglie in the 1920s). Faced with the measurement problem, Bohm—"explicitly influenced by … EPR" (Ney 2013a, p. 29)—decided to add new physics to the wave function i.e. actual configurations of particles (Goldstein 2013).

According to Bohm's theory, a full description of a physical system would be its wave function—reconstituted as an "ontological pilot wave (a complex-valued field in configuration space)" (Valentini 2010, p. 476)—supplemented by additional variables which specify the positions of the particles which make it up (and which constitute the real, 'primitive' ontology).[43] Bohmian mechanics's ontology is thus dualistic insofar as it is committed to the existence of both the wave function *and* particles (Ney 2013a, p. 38). These particles exist in the 3-dimensional space that we all experience whereas the wave function 'lives on' abstract 'configuration space' (Valentini 2010, p. 484). The wave function

[43] "The wave function would seem to be part of the ontology. It's real in that sense. It's not subjective in Bohmian mechanics—it has a rather real role to play: it has to govern the motion of the particles. But it's not part of the primitive ontology. Bohmian mechanics is fundamentally about particles and their motions, and not wave functions." (Goldstein and Zanghì 2013, p. 94)

describes “the state of the [pilot] wave [where the] role of this wave is to guide the particle into various states” (Ney 2013a, p. 30) in a precise (i.e. deterministic) way (Bacciagaluppi 2012). There is therefore nothing random about the evolution of Bohmian systems. According to the Bohmian view, the particles which make up physical systems always have definite positions and trajectories in the classical sense (Callender 2009).

Because Bohmian mechanics is fundamentally a theory which describes how configurations of particles change their positions in time, first-order in or fundamental to the Bohmian description is the velocity of the particles i.e. the rate of change in their positions (Goldstein 2013). So in addition to the Schrodinger equation Bohmian mechanics adds “an equation of motion for the positions” (Goldstein and Zanghì 2013, p. 93) of the particles known as the ‘guiding equation’

$$\frac{dQk}{dt} = \left(\frac{\hbar}{mk}\right) \mathrm{Im}\ \frac{\psi{*}\delta k}{\psi{*}\psi}\ (Q_1, \ldots, Q_N)$$

which “expresses the velocities of the particles in terms of the wave function” (Goldstein 2013).

To bring it back to the double-slit experiment: the Bohmian explanation of the motion responsible for the interference pattern built up through repeated iterations of the double-slit experiment is that, insofar as Bohmian mechanics describes particles’ motions via postulating that particles are guided by waves, then the interference pattern is understood to be impressed on the particle by the wave. Although the particle definitely travels through one slit only, the wave travels through both slits, generating interference—because the slits cause the amplitudes of wave to overlap—yet this wave still guides the motion of the particle in line with the observed interference pattern: the particle hits most often where the amplitudes reinforce and never where the amplitudes cancel out, and so on (Goldstein 2013).

Bohmian mechanics is a mechanical theory without observers or collapse which nevertheless returns the correct probabilities for measurement outcomes of quantum mechanics once its dynamical equations are analysed. According to Bohmians it turns out after analysis that the pilot wave + particle description returns all the standard predictions of quantum mechanics: the wave functions naturally as a probability wave which returns the correct probabilities for measurement outcomes in quantum experiments insofar as it always guides the particle in line with the predictions of standard quantum mechanics (Goldstein 2013). So although a deterministic theory, the apparent stochasticity of measurement outcomes arises on the Bohmian picture as a consequence of the pilot wave / guiding equation framework (Goldstein 2013).

Bohmians thus solve the measurement problem without "making the concept of a measurement or observation part of the fundamental laws" (Ney 2013a, p. 30) by identifying the values registered in definite measurement outcomes (e.g. 'pointer states' of measuring devices) with the 'hidden variables' (positions of particles) postulated alongside the wave function (Goldstein 2013).[44] So according to Bohmians, we never observe the superposition states entailed by the standard linear quantum dynamics because, on their theory, entities "always have determinate locations" (Ney 2013a, p. 30). Bohmians argue that the *appearance* of collapse in measurement contexts reflects a change in the pilot wave's role in determining the motions of the particles: the amplitudes of the wave which are no longer relevant to the particles' evolution can be discarded as extraneous to their description since the trajectories of the particles ultimately

[44] Nevertheless Bohmian mechanics *only* gives the probabilities for measurement outcomes for position states insofar as the only explicit observables in Bohmian mechanics are the positions of pointers on measuring devices (Goldstein 2013). For example, according to Bohmian mechanics, "spin operators [do not] correspond to genuine properties of … particles" (Goldstein 2013).

position them in a distinct configuration in support of the observed measurement outcome (Bacciagaluppi 2012) rather than some other. In these contexts, the symmetry between the amplitudes of the wave describing superpositions of measurement outcomes is broken (Allori 2013, pp. 67-68), leading to apparent collapse, “reflecting the sudden irrelevance … of some part of the wavefunction in its influence on [the] variables” (Saunders 2010, pp. 4). Thus:

> “In the case of measurements, Bohm argued that the wave function evolves into a superposition of components that are and remain separated in the total configuration space of measured system and apparatus, so that the total configuration is ‘trapped’ inside a single component of the wave function, which will guide its further evolution, as if the wave had collapsed (‘effective’ wave function).” (Bacciagaluppi 2012)

That is, the extraneous amplitudes can simply be discarded and “once irrelevant in this way [are] always irrelevant…. This explains the appearance of collapse” (Saunders 2010, p. 4) insofar as it is easy to predict the observed measurement outcome in the evolution of the physical system (Goldstein 2013).

As for Schrodinger’s cat: similarly to how its states would be represented according to classical mechanics, Schrodinger’s cat is always *either* alive *or* dead according to Bohmians “since … getting a cat to come out either alive or dead demands that the particles end up in one or another configuration” (Maudlin 2010, p. 131)

Insofar as in Bohmian mechanics the ‘primitive ontology’ is configurations of “particles [which] always possess determinate locations in three-dimensional space” (Ney 2013a, p. 38), then “the … positions of all particles yield the familiar picture of the (single) world we are aware of” (Vaidman 2014) and so it is relatively easy to secure the connections between the manifest image of everyday experience and the scientific image of nature provided by this picture, since:

> "Bohmian mechanics has no trouble accounting for our initial opinions about a world of localized objects in a low-dimensional spacetime because it postulates a world of localized microscopic objects in a low-dimensional spacetime which behave, in gross, as we take the world to." (Maudlin 2010, p. 139)

Part 4: Interpretation evaluation

Although they entail drastically heterogeneous metaphysical pictures of reality, Bohmian mechanics and pure wave mechanics are empirically equivalent, and due to this quantum mechanics is arguably underdetermined by empirical evidence. Because of this underdetermination, for naturalized ontology these interpretations must be evaluated on extra-empirical lines via the theoretical virtues of 'parsimony' and 'explanatory power'.

4.1: Explanatory power

According to David Wallace, considerations from relativistic physics make hidden variables theories such as Bohmian mechanics questionable:

> "For technical reasons (originating, for the most part, in relativistic quantum physics) [hidden variables theories are] actually pretty questionable in modern physics." (Wallace 2013, pp. 7-8)

In particular, Bohmian mechanics is empirically adequate only for non-relativistic phenomena (Callender 2009). For example, the velocity of a particle in an entangled Bohmian system can be dependent on the states of spatially-separated particles e.g. in the EPRB singlet state, and due to this "non-local dynamics of Bohmian particle positions" (Vaidman 2014)—insofar as the Bohmian guidance equation seems to presuppose 'absolute simultaneity' (Ney 2013a, p. 45)—Bohmian mechanics explicitly violates a fundamental principle of relativistic theory—Lorentz invariance[45]—making it unable to explain the full range of quantum phenomena, for example quantum field theory.

4.1.1: Bell's inequalities

The technical reasons that make hidden variables theories such as Bohmian mechanics questionable in the context of modern physics mentioned by Wallace are due to a theorem given by the physicist John Stewart Bell which places severe constraints on the form any 'hidden variables' theory of quantum mechanics can take. 'Bell's theorem' in a nutshell is the proposition that no local hidden variables physical theory will be in empirical agreement with all the statistical predictions of quantum mechanics. In the years since Bell gave his theorem it has been put to the test many times and these tests have supplied physics and philosophy with a family of results that have come to be known as 'Bell's inequalities' which more generally are a collective name for a family of results derived from testing local hidden variables—i.e. theories which assume hidden variables + locality—conceptual frameworks (Bub 2015).

Utilizing the same sort of dialectical set-up as Bohm's version of the EPR thought experiment (EPRB), Bell argues that, given particular assumptions—such as 'locality' and 'separability'—EPRB correlations obey a number of mathematical constraints known as 'Bell's inequalities' (Bell 1964). However quantum mechanics's predictions violate these constraints and this can be empirically demonstrated insofar as it is possible to set experiments up to test whether the constraints hold when quantum mechanics predicts that they

[45] "Bohmian mechanics and special relativity, a central principle of physics, are not compatible: Bohmian mechanics is not Lorentz invariant. Nor can it easily be modified to accommodate Lorentz invariance. Configurations, defined by the simultaneous positions of all particles, play too crucial a role in its formulation, with the guiding equation defining an evolution on configuration space." (Goldstein 2013)

shouldn't. When such experiments are run they invariably confirm that quantum mechanics does indeed violate the EPRB constraints—and so confirm that quantum mechanics is 'inequal' to 'local realist' (i.e. local hidden variables) theories (Shimony 2009):

> "What Bell showed was that the statistical correlations between the measurement outcomes of suitably chosen different quantities on [entangled] systems are inconsistent with an inequality derivable from Einstein's separability and locality assumptions — in effect from the assumption that the correlations have a common cause." (Bub 2015)

In order to derive his inequalities, Bell first formulates an example of a local hidden variables framework. This framework consists of two pairs of systems, where the individual systems that constitute each pair are each designated '1' and '2'. Because Bell is considering a local hidden variables framework, each pair is described by a single 'complete state' 'm' which specifies the totality of the pair's properties. The way the wave function of each entangled pair is generated makes the complete state of the pair, after they separate, independent of the properties of the individual systems which make up the pair. Measurements on '1' can take the value 1 or 2; likewise for measurements on '2', and the probabilities for measurement outcomes on these systems always add up to unity (Bub 2015).

A key concept within Bell's local hidden variables framework is 'locality', which consists of the conjunction of two independence conditions:

1) Remote outcome independence: given the total state 'm' of the pair, the measurement outcome on '1' predicts no information about measurement outcomes on '2', and vice-versa.

2) Remote context independence: the parameters of '1' and '2' are independent of eachother.

This conjunction of independence conditions is known as ‘Bell’s locality’ (Bub 2015) and they roughly mirror the EPR local hidden variables assumptions.

Next, Bell uses his ‘locality’ in order to derive ‘Bell’s inequality’, which as mentioned previously is a mathematical constraint which bounds the possible probabilities for measurement outcomes on ‘1’ and ‘2’ (Bub 2015).

Finally, Bell demonstrates that quantum mechanics violates his inequality via formulating a quantum system whose wave function’s probabilities for measurement outcomes are empirically inconsistent the EPR assumptions (Bub 2015). This quantum system is made up of a pair of entangled photons ‘1’ and ‘2’ described by a single wave function where, before measurement, the state of the two photon system can be expressed as a superposition of linear polarization states, i.e., where 1 exists in a superposition of ‘linearly polarized in x-direction’ + ‘linearly polarized in y-direction’, and likewise for 2 (Bub 2015). Because they are entangled, the potential measurement outcomes on these photons are correlated: if 1 is measured to be polarized in x-direction then 2 will be measured to be in y-direction, and vice-versa (Bub 2015). In Bell’s experimental set-up[46], the photon pairs are emitted from a light source, whereafter the states of the photons are measured by polarization analyzers. The measurement outcome is ‘1’ when a photon’s polarization direction is in the direction of the ‘transmission axis’ and thus emerges from the analyzer in the ‘ordinary ray’ whereas the measurement outcome is ‘-1’ when a photon’s polarization direction is perpendicular to the transmission axis and thus emerges from the analyzer in the ‘extraordinary ray’ (Bub 2015). Bell concludes that if you

[46] Although Bell’s argument that quantum mechanics violate his inequality was originally developed as a thought experiment, it has been experimentally tested and verified many times since its formulation, most notably in 1982 by Aspect, Granger, and Roger, whose experimental set-up was the first to utilize polarization analyzers with two exit channels and thus realize Bell’s conceptual scheme as exactly formulated.

use the quantum mechanical wave function to calculate the probabilities that photons 1 and 2 emerge from the polarization analyzers in the ordinary ray or extraordinary ray you find that the probabilities for measurement outcomes violate his inequality. The results of this experiment thus agree with quantum mechanics and disagree with local hidden variables theories (Bub 2015). In other words, the observed experimental statistics “agreeing with the quantum mechanical predictions constitute a refutation of Bell's Inequality and hence of the family of Local Realistic Theories.” (Bub 2015)

Although Bell proved that quantum mechanics is in empirical conflict with the EPR (local hidden variables) assumptions, the exact interpretation of the violation of his inequalities is controversial due to the number of assumptions involved. For example, according to Ghirardi “[i]n view of the experimental violation of Bell's inequality, one has to give up either or both of [the EPR] assumptions” (Ghirardi 2011)—i.e. give up locality, or separability, or both. However it is not *necessary* to give up either of these assumptions on *all* interpretations, as will be become clear. Nevertheless, there are two main—conflicting—ways of interpreting Bell’s inequalities with regard to the EPR assumptions.

One way of interpreting Bell’s theorem is that it proves that measurements on entangled physical systems suggest some form of *nonlocal* hidden variables theory. For example, as an explicitly nonlocal hidden variables theory, there is ‘spooky action at a distance’ built into the very structure of Bohmian mechanics insofar as the pilot wave changes instantaneously and nonlocally when measurements are performed on elements in entangled systems:

> “[W]hen Bohm derives the statistical predictions of a Quantum Mechanically entangled system whose constituents are well separated, the outcome of a measurement made on one constituent depends upon

> the action of the "guiding wave" upon constituents that are far off, which in general will depend on the measurement arrangement on that side." (Shimony 2009)

Indeed, the development of Bohmian mechanics "inspired Bell to take seriously the hidden variables interpretation of Quantum Mechanics, and the nonlocality of this model suggested his theorem." (Shimony 2009) Proponents of Bohmian mechanics are thus prepared to sacrifice a principle central to modern physics—locality—in order to secure that quantum systems have definite realities. The interpretation of the observed violations of Bell's inequalities that Bohmians are prepared to accept is thus that they proves that entangled correlations in physical systems entail nonlocality:

> "It used to be widely believed that the pilot-wave theory of … Bohm … had been ruled out by experiments demonstrating violations of Bell's inequality. Such misunderstandings have largely been overcome, and in recent times the theory has come to be widely accepted by physicists as an alternative (and explicitly non-local) formulation of quantum theory." (Valentini 2010, p. 477)

On the other hand, some argue that this explicit invocation of nonlocality a sign that the unnecessary extra physics is on the wrong track, insofar as this extra physics makes Bohmian mechanics incompatible with Special Relativity; besides such an implication goes against EPR's original motivation for postulating hidden variables in the first place (i.e. in order to 'fix' what they saw as quantum mechanics's apparent incompatibility with Special Relativity):

> "[W]hen Bell's predictions were confirmed, this established that EPR's suggestion that the quantum state is incomplete would not suffice to eliminate quantum nonlocality." (Ney 2013a, p. 20)

The objection goes like this: Bell's theorem ensures that hidden variables theories such as Bohmian mechanics must necessarily be nonlocal due to violating Lorentz-invariance:

> "In a theory in which parameters are added to quantum mechanics to determine the results of individual measurements, without changing the statistical predictions, there must be a mechanism whereby the setting of one measuring device can influence the reading of another instrument, however remote. Moreover, the signal involved must propagate instantaneously, so that a theory could not be Lorentz invariant." (Bell 1984)

Thus Bohmian mechanics conflicts not just in spirit but in principle with Special Relativity, and thus quantum mechanics's relativistic extensions, such as quantum field theory, all the way up to the Standard Model, etc. The explicit nonlocality built into Bohmian mechanics which makes it incompatible with Special Relativity thus means that it lacks explanatory power, insofar as it cannot explain the whole gamut of quantum phenomena. So, although Bohmian mechanics arguably does explain the emergence of the manifest image in a limited sense, it nevertheless should be noted that the theory of Special Relativity is also a very well-confirmed aspect of the empirical world (insofar as it has been experimentally tested to hell and back, and as far as we know hasn't made any predictions in conflict with experience), and insofar as Bohmian mechanics can't explain such relativistic phenomena, it lacks the theoretical virtue of 'explanatory power':

> "Bohmian mechanics does not account for phenomena such as particle creation and annihilation characteristic of quantum field theory. This is not an objection to Bohmian mechanics but merely a recognition that quantum field theory explains a great deal more than does nonrelativistic quantum mechanics, whether in orthodox or Bohmian form." (Goldstein 2013)

Thus another way of interpreting the ramifications of Bell's argument is that since any hidden variables theory must be explicitly nonlocal insofar as observed violations of Bell's inequalities means that the values of any hidden variables (what EPR refer to as a physical system's 'elements of reality') cannot be locally determined, then this makes it less likely that the wave function merely provides incomplete knowledge about some definite, underlying reality, and more likely that the standard, unitary quantum formalism is actually correct instead.[47] This is the interpretation Everettians are prepared to accept insofar as pure wave mechanics doesn't violate Lorentz invariance and is thus compatible with relativistic extensions of quantum mechanics, and so on.[48] Pure wave mechanics is thus a good deal more explanatorily powerful than theories of quantum mechanics which are not able to be extended to the relativistic domain such as Bohmian mechanics.

4.2: Parsimony

The idea of parsimony as a theoretical virtue is often cashed out in terms of the principle of 'Occam's razor', i.e. the principle that 'plurality should not be posited without necessity'[49]. In practice what Occam's razor entails is that, when you are faced with a choice between multiple explanations for some phenomenon, then

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[47] A result related to Bell's theorem: "The Kochen-Specker Theorem … [shows] that any hidden-variables formulation of quantum mechanics must be contextual. It must violate the noncontextuality assumption "that measurement of an observable must yield the same value independently of what other measurements may be made simultaneously" (Bell 1987, p. 9). To many physicists and philosophers of science contextuality seems too great a price to pay for the rather modest benefits — largely psychological, so they would say — that hidden variables provide." (Goldstein 2013)

[48] "The MWI allows for a local explanation of our Universe. The most celebrated example of nonlocality given by Bell 1964 in the context of the Einstein-Podolsky-Rosen argument cannot get off the ground in the framework of the MWI because it requires a predetermined single outcome of a quantum experiment, see discussion in Bacciagaluppi 2002. There is no action at a distance in our Universe, but there is an entanglement. And a "world" is a nonlocal concept. This explains why we observe non-local correlations in a particular world." (Vaidman 2014)

[49] *Pluralitas non est ponenda sine necessitate.*

the simplest explanation (i.e. the one which posits the fewest entities) is the one you should pick. Put more quantitatively: according to probability theory measures (e.g. Kolmogorov complexity, or Minimum Message Length), if a theory is less parsimonious, then it is less likely to be true insofar as—to put it very simply—the conjunction of x and y is less likely to exist than just x.

A common criticism of pure wave mechanics follows from the supposition that, although in practice an observer will never experience the other branches of the wave function, they should nevertheless be considered “operationally real” (Everett 1956, p. 150) insofar as quantum interference requires always treating the other terms in a superposition as having observational consequences, i.e., because the existence of these other branches is necessitated by the linear dynamics in order to explain interference effects (Barrett 2014). Because decoherence couples each localized component of macroscopic objects in superposition states to different states of the environment, a consequence of this is that each possible degree of freedom of a physical system can be coupled to the environment, ultimately leading to entangled superposition states of many, many, many distinct terms (Bacciagaluppi 2012). This means that the wave function of the entire universe is composed of an extremely large macroscopic superposition of branches and represents an ‘ontological multiplicity’ (Wallace 2013, p. 8) of ‘worlds’.

Critics use these facts to argue that pure wave mechanics is an egregiously unparsimonious theory. However these ‘many worlds’ are not additional posits on this theory; nothing is added to the unitary ontology of the wave function evolving solely according to the linear dynamics; you actually have to *modify* the unitary theory in order to *get rid* of them (via adding some arbitrary collapse postulate, or ‘hidden variables’, for example), which clearly violates the spirit of Occam’s razor. As Lev Vaidman explains:

> "It seems that the majority of the opponents of the MWI reject it because, for them, introducing a very large number of worlds that we do not see is an extreme violation of Ockham's principle: "Entities are not to be multiplied beyond necessity". However, in judging physical theories one could reasonably argue that one should not multiply physical laws beyond necessity either (such a version of Ockham's Razor has been applied in the past), and in this respect the MWI is the most economical theory. Indeed, it has all the laws of the standard quantum theory, but without the collapse postulate, which is the most problematic of the physical laws. The MWI is also more economic than Bohmian mechanics, which has in addition the ontology of the particle trajectories and the laws which give their evolution." (Vaidman 2014)

Regarding Vaidman's last point: insofar as Bohmian mechanics is committed to "a dual ontology: the configuration q(t) together with the pilot wave $\Psi[q,t]$" (Valentini 2010, p. 483), it is arguably less parsimonious than pure wave mechanics which is wave function monism, and thus less likely to be a true description of reality. A related objection is that, because hidden variables theories such as Bohmian mechanics modify the quantum ontology via postulating additional parameters alongside the standard quantum ontology and dynamics, some have criticised such approaches "on the basis that, being empirically indistinguishable from quantum mechanics, such [approaches are] an example of 'bad science' or of 'a degenerate research program'." (Ghirardi 2011)[50]

Ultimately, it is arguably the job of science to develop the simplest, most powerful theory that fits all the data: to that end, you don't tabulate the ontological extravagance of a theory which explains a given set of data by counting the overall number of entities (e.g. 'worlds'); you tabulate it by counting

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[50] See also Brown and Wallace's objection to Bohmian mechanics which is that such a view differs from Many-Worlds only insofar as it posits one extra entity—the so-called 'world particle', and thus may be considered a sort of 'Many-Worlds in denial' (Ney 2013a, p. 43).

the number of distinct equations, and pure wave mechanics requires the fewest number of equations to explain the whole range of quantum mechanical phenomena. Evaluated along these lines, i.e. along the lines of objective criteria for theory choice in cases of underdetermination such as parsimony and explanatory power, pure wave mechanics is clearly the most virtuous theory in a physical sense, insofar as it possesses the most explanatory power among quantum interpretations while at the same time depending on the fewest theoretical presuppositions i.e. ‘baggage’ (Tegmark 2008) required to explain quantum phenomena. That is, pure wave mechanics gives you the most ‘bang for your buck’ insofar as it postulates just the minimal physical structure necessary to in order to explain all the experimental outcomes that are inexplicable classically e.g. interference patterns in double-slit experiments, quantum entanglement, and so on.

Yet, as mentioned previously, pure wave mechanics also entails a potentially infinite number of absurdities insofar as, on this view, the evolution of the wave function according to the unbroken Schrodinger dynamics leads to the actualization of every possible measurement outcome. Perhaps this should lead us to consider the negation of a proposition we assumed was true at the beginning of essay, namely wave function realism. Either that or arbitrarily pick a clearly deficient realistic theory in the form of Bohmian mechanics. So let us consider that the wave function does not represent the reality of physical systems after all.

Part 5: Wave function (anti-)realism?

Richard Feynman's 'path integral' formulation of quantum mechanics is an example of an anti-realist interpretation of quantum mechanics which nevertheless makes *instrumental* use of the wave function insofar as it explicitly makes use of all its amplitudes in its calculations for measurement outcomes in quantum experiments. For example in the context of the double-slit experiment, for Feynman's path integral formulation *every possible amplitude* of the photon which—theoretically, at least—describes every possible path it can take through the slits on its way to the photographic plate is used to calculate the final outcome i.e. the observed interference distribution. Feynman, regarding such interference effects, suggests the following:

> "How does it really work? What machinery is actually producing this thing? Nobody knows any machinery. Nobody can give you a deeper explanation of this phenomenon than I have given; that is, a *description* of it." (Feynman 1967, p. 145, emphasis added)

More generally, anti-realist or instrumentalist approaches to quantum mechanics, such as 'epistemic' interpretations—where, for example, the amplitudes of the wave function merely encode the (lack of) knowledge you have about a physical system, such as the probabilites that you will find it in a particular state when you measure it—all share one crucial feature: according to such interpretations, the wave function does not represent the objective reality of physical systems. If the wave function does not represent the reality of physical systems, then this means that the absurdities implied by pure wave mechanics are nothing more than mere fictions, errors which arise only if one makes the mistake of taking the wave function to be more than simply an instrument to calculate the probabilities for measurement outcomes in quantum experiments. Such a stance about quantum mechanics is eloquently summed up in the following phrase, coined by the physicist David Mermin: “Shut up and calculate!” (Mermin 1989, p. 9)

Although some have argued that “[q]uantum state probabilities do not allow for an ignorance interpretation [insofar as] they are ontic probabilities” (Lyre 2010, p. 1432), prima facie it seems unlikely whether one could prove either way whether the wave function represents the reality of physical systems or merely (lack of) knowledge about them. However recently an experiment was set up to test claims made by realists such as the above, the results of which seemingly rule out a broad class of these instrumental interpretations of quantum mechanics. In a paper entitled ‘Measurements on the reality of the wavefunction’, the physicists Martin Ringbauer et. al. argue that they have experimentally demonstrated a phenomenon which proves (or at least suggests) the following proposition about the ontological status of the wave function:

> “[N]o knowledge interpretation can fully explain the indistinguishability of non-orthogonal quantum states in three and four dimensions. Assuming that some underlying reality exists, our results strengthen the view that the entire wavefunction should be real.” (Ringbauer et. al. 2015, abstract)

Ringbauer et. al.’s experiment concerns measurements on photons which are prepared in superpositions of non-orthogonal[51] vertical and diagonal polarization states. They argue that if the photons’ polarization states could not determined exactly then that would mean that they really are in superpositions of vertical and diagonal polarization states, rather than being ‘actually’ in some definite (although unknown) states. This would thus suggest that the photons’ wave functions correspond to their reality. Conversely, if the photons’ polarization states could be exactly determined, then this would suggest that they always have definite polarisation states and therefore that their wave functions

[51] i.e. where the states are not opposites of eachother.

represent mere lack of knowledge about some definite (although unknown) underlying states, and thus do not represent the reality of the photons. Once the experiments were performed Ringbauer et. al. found that they could not glean enough information to exactly determine the polarization states of the photons which suggested that they were superpositions rather than definite states after all. Ringbauer et. al. conclude that this shows that the wave function is in direct correspondence with the objective reality of quantum systems rather than representing mere (lack of) knowledge about them, as anti-realist, instrumental, or epistemic interpretations of the wave function would have it (Ringbauer et. al. 2015).

Seemingly, our way out of the present quandary is blocked: if the wave function cannot be regarded as being merely epistemic, i.e. as representing our knowledge about quantum systems rather than anything ontological or objective, then this means that we are stuck with a physical theory which is essentially absurd—remember pure wave mechanics's elephant in the room! Either that, or we can decide to go with a theory which is demonstrably less theoretically virtuous: Bohmian mechanics.

Part 6: Conclusion

In this essay I have argued that assuming that the best interpretation of our best physical theory represents reality entails a multitude of absurdities. In a shallow way, this has the dialectical structure of something like a reductio ad absurdum argument: assuming wave function realism allows you to derive an absurdity. However I have also shown that we are prevented from taking this assumption's negation—wave function anti-realism—by a convincing argument in the recent physics literature.

In the introduction to this essay, I mentioned that the guiding question of naturalized ontology is:

> What does quantum mechanics (as our best physical theory) say about the nature of reality in the most general sense?

In other words, the investigation guiding the course of this essay has been to figure out what the most general thing one can say about the nature of the reality according to quantum mechanics is. After careful consideration, the answer that I have landed on—for better or worse—is the following: (our best interpretation of) quantum mechanics says that reality is absurd.

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